

+  
TJ 260  
G78

MINISTRY OF MUNITIONS  
AND  
DEPARTMENT OF SCIENTIFIC AND  
INDUSTRIAL RESEARCH

---

Technical Records of  
Explosives Supply  
1915-1918

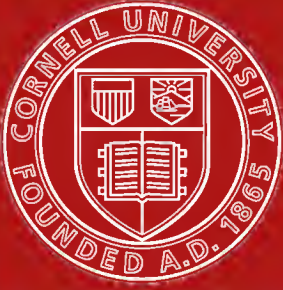
---

No. 9  
HEAT TRANSMISSION



Published for the Department  
of Scientific and Industrial Research by  
His Majesty's Stationery Office

1922



## Cornell University Library

The original of this book is in  
the Cornell University Library.

There are no known copyright restrictions in  
the United States on the use of the text.

Cornell University Library  
TJ 260.G78  
Technical records of explosives supply,  
  
3 1924 004 360 446 engr

**BASEMENT STORAGE**



# TECHNICAL RECORDS OF EXPLOSIVES SUPPLY

## VOLUME NO. 9—HEAT TRANSMISSION.

### *Errata.*

Page 1, bottom line, equation to read  $\log \frac{b}{a} = \frac{b-a}{a}$  nearly.

„ 9, line 14, for  $t_1$  read  $t$ .

„ 12, line 16, equation to read  $t' - t = (t'_0 - t_0)e^{-(n-1)\lambda x}$ .

„ 12, line 21, equation to read  $t_0 - t = \frac{t'_0 - t_0}{n-1} (1 - e^{-(n-1)\lambda x})$ .

„ 12, line 22, equation to read  $t'_0 - t = \frac{n}{n-1} (t'_0 - t_0) (1 - e^{-(n-1)\lambda x})$ .

„ 20, table headed Air Cooling, for Therma capacity C.H.U. read Thermal capacity C.H.U.

„ 26, line 5, for gives read give.

„ 32, line 35, for affect read effect.

„ 36, bottom line, equation to read  $v = 298 \sqrt{\frac{h}{30}}$ .

„ 43, line 1, for  $\cdot 0415 = 0\cdot 408$  read  $\cdot 0415 \times 0\cdot 408$ .

„ 43, line 4, read  $0\cdot 014756$  lb.

„ 43, line 6, for  $\cdot 014756 = 1035$  read  $\cdot 014756 \times 1035$ .

„ 44, line 10, following Table 7a, read  $\frac{5\cdot 1 \times 1000}{3\cdot 91 \times 60 \times 60}$ .

„ 46, line 10, read  $\cdot 01341 \times 1035 = 13\cdot 88$  B.Th.U.

Fig. 9, facing page 29, read Coefficients.



MINISTRY OF MUNITIONS  
AND  
DEPARTMENT OF SCIENTIFIC AND  
INDUSTRIAL RESEARCH

---

Technical Records of  
Explosives Supply  
1915-1918

---

No. 9

HEAT TRANSMISSION

---



LONDON :

Published for the Department of Scientific and Industrial Research by  
HIS MAJESTY'S STATIONERY OFFICE, and to be obtained from the  
addresses given on the back of the cover.

---

1922

NEW YORK  
D. VAN NOSTRAND COMPANY  
EIGHT WARREN STREET

The following reports dealing with other aspects of the work of the Department of Explosives Supply have already been published by His Majesty's Stationery Office :—

SECOND REPORT ON COSTS AND EFFICIENCIES FOR H.M. FACTORIES CONTROLLED BY FACTORIES BRANCH, DEPARTMENT OF EXPLOSIVES SUPPLY. Price 7s. 6d. (*by post* 8s.). *This report also contains most of the general information originally included in the First Report on Costs and Efficiencies, issued by the Ministry of Munitions, and now out of print.*

REPORT ON THE STATISTICAL WORK OF THE FACTORIES BRANCH. Price 4s. 6d. (*by post* 5s.).

PRELIMINARY STUDIES FOR H.M. FACTORY, GRETNA, AND STUDY FOR AN INSTALLATION OF PHOSGENE MANUFACTURE. Price 15s. (*by post* 16s.).

Copies of the above and of the present series of reports may be obtained through any bookseller or direct from H.M. Stationery Office at the addresses given on the back of the cover.

## PREFATORY NOTE

This is the ninth and last of a special series of reports which have been published in order to make available, for the benefit of the industries concerned, results of scientific and industrial value contained in the technical records of the Department of Explosives Supply of the Ministry of Munitions (*see list below*). The work recorded in these Reports was done at, or in connexion with, some of the National Factories during the war. The preparation of the necessary abstracts of information was begun by the Ministry of Munitions at the close of the war, and arrangements were afterwards made by the Department of Scientific and Industrial Research to complete them. The Department wish it to be clearly understood that the interesting information contained in this series of reports is the result of the labours of the Ministry of Munitions, and has been compiled by Mr. W. Macnab, C.B.E., F.I.C., an officer of that Ministry attached to the Department for this work. Professor A. W. Porter, D.Sc., F.R.S., has been good enough to supervise the preparation of the present report and to draw up those portions of it relating to the theoretical aspect of the subject.

Department of Scientific and Industrial Research,  
16 and 18 Old Queen Street,  
London, S.W.1.

July, 1922.

### *Previous volumes in this series :—*

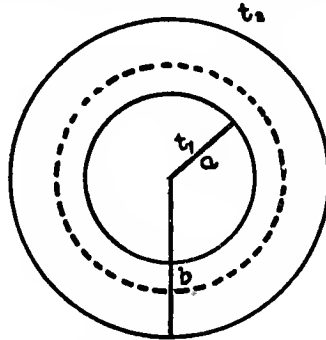
- NO. 1. RECOVERY OF SULPHURIC AND NITRIC ACID FROM ACIDS USED IN THE MANUFACTURE OF EXPLOSIVES: DENITRATION AND ABSORPTION. Price 12s. 6d. (*by post* 13s.).
- NO. 2. MANUFACTURE OF TRINITROTOLUENE (TNT) AND ITS INTERMEDIATE PRODUCTS. Price 17s. 6d. (*by post* 18s.).
- NO. 3. SULPHURIC ACID CONCENTRATION. Price 12s. (*by post* 12s. 7d.).
- NO. 4. THE THEORY AND PRACTICE OF ACID MIXING. Price 12s. (*by post* 12s. 6d.).
- NO. 5. MANUFACTURE OF SULPHURIC ACID BY CONTACT PROCESS. Price 25s. (*by post* 26s.).
- NO. 6. SYNTHETIC PHENOL AND PICRIC ACID. Price 15s. (*by post* 15s. 7d.).
- NO. 7. MANUFACTURE OF NITRIC ACID FROM NITRE AND SULPHURIC ACID. Price 10s. (*by post* 11s.).
- NO 8. SOLVENT RECOVERY. Price 3s. (*by post* 3s. 3d.).

# CONTENTS

|                                                                                                     | PAGE      |
|-----------------------------------------------------------------------------------------------------|-----------|
| <b>THEORETICAL SECTION</b>                                                                          | <b>I</b>  |
| Fundamental principles                                                                              | I         |
| Criterion for turbulence                                                                            | 4         |
| Determination of coefficients of transmission                                                       | 5         |
| Application of method of dimensions                                                                 | 6         |
| Application of coefficient of transmission to specific problems                                     | 9         |
| Construction of alignment charts                                                                    | 14        |
| <b>EXPERIMENTAL SECTION</b>                                                                         | <b>16</b> |
| Method of investigation                                                                             | 17        |
| First series                                                                                        | 18        |
| Examination of experimental results                                                                 | 20        |
| Second series                                                                                       | 21        |
| Acid coolers at Queen's Ferry                                                                       | 27        |
| Water economy and efficient cooling                                                                 | 27        |
| Lead coolers in denitration plant                                                                   | 28        |
| Superheater at denitration plant                                                                    | 30        |
| The effect of stirring                                                                              | 32        |
| Surface condensers                                                                                  | 34        |
| Heat interchange in a cylinder in which a heat-producing reaction takes place                       | 35        |
| Surface loss                                                                                        | 35        |
| <b>APPLICATION OF THE PRINCIPLE OF QUINAN'S BUBBLER-SCRUBBER TO THE COOLING OF CONDENSING WATER</b> | <b>36</b> |
| Amount of air passed through $\frac{1}{8}$ -in. diameter hole for various pressure differentials    | 36        |
| Velocities for various pressure differentials                                                       | 37        |
| Volume of air which will pass through plate                                                         | 37        |
| Temperature gradient of water passing over 1 ft. length of plate for various velocities             | 39        |
| Air efficiency                                                                                      | 44        |
| Air required to cool 1,000 lb. water per hour                                                       | 45        |
| Power required                                                                                      | 45        |
| Summary                                                                                             | 45        |
| Example                                                                                             | 45        |
| <b>ALIGNMENT CHARTS</b>                                                                             |           |
| Over-all coefficient of transmission                                                                | 3         |
| Coefficient of transmission for pipes carrying water                                                | 8         |
| " " " " " " gases                                                                                   | 8         |
| To find economic length of pipe                                                                     | 11        |

## THEORETICAL SECTION.

**Fundamental principles.**—One of the most important physical problems in factory practice is concerned with the laws governing the flow of heat through the walls of pipes. For example, when heat is produced in a chemical reaction, the mixture so heated can be cooled by letting it flow slowly through a tank in which coils of pipe are placed, these pipes carrying cold water; or, on the other hand, it may be necessary to raise the temperature of a reacting mixture to a point at which the desired reaction proceeds most advantageously. This can be effected by means of steam passed through pipes contained in the mixture. The same kind of problem enters in the case of steam condensers in ordinary engineering practice. A great many varieties of cases present themselves for consideration. The property of a material which specifies its power of conducting heat is the thermal conductivity  $K$ . It is defined as the heat transferred in unit time across unit area when the gradient of temperature is unity; *i.e.*,  $H = KAG \times \text{time}$ . In dealing with the transmission through pipes it is advantageous to specify instead a quantity introduced by Kelvin and called the coefficient of transmission  $\kappa$ . This is defined as follows: Let the temperatures just inside and just outside the wall of



the pipe be  $t_1$  and  $t_2$  respectively. Let the temperature at any intermediate distance  $r$  from the axis be  $t$ . When the temperature is steady the same amount of heat must flow through each cylindrical surface, *i.e.*:

$$-K \ 2\pi r.l \ \frac{\partial t}{\partial r} = \frac{H}{\text{time}} = \text{constant};$$

where  $l$  is the length of the pipe, whence

$$t = - \frac{H}{K \ 2\pi l \times \text{time}} \log r + \text{constant}.$$

Putting  $r$  successively equal to  $a$  and  $b$  and  $t$  equal to  $t_1$  and  $t_2$ , and subtracting

$$t_1 - t_2 = \frac{H}{K 2\pi l \times \text{time}} \log \frac{b}{a}.$$

When the pipe wall is thin

$$\log \frac{b}{a} = \frac{b - a}{a} \text{ nearly}$$

so that

$$t_1 - t_2 = \frac{H(b-a)}{K 2\pi a.l \times \text{time}}$$

where  $2\pi a.l$  is the area of the surface of the pipe. Hence

$$H = \frac{K}{b-a} A (t_1 - t_2) \times \text{time}.$$

The flow of heat is therefore proportional to the difference of temperature, inside and out, to the time, area, and to the quantity  $K/(b-a)$ . This last quantity is the coefficient of transmission. It is the amount that flows through each area in unit time when unit *difference* of temperature exists between inside and outside. It is measured in Centigrade-heat-units (C.H.U.) per hour per square foot per degree centigrade difference of temperature.

If the temperature of the pipe wall, at inside and outside surface, were known it would be a very easy matter to calculate the flow. All that is usually known, in practice, is the average temperature of the liquid flowing. There is, necessarily, a gradient of temperature across the liquid when heat is being transmitted, and this is often very great near the metal surface. Practically the whole of the difficulty of the problem is concerned with this fact; because it becomes necessary to calculate the distribution of temperature across the liquid or gas on each side of the pipe wall. This distribution varies very much from one case to another. If the fluid is moving very fast, all except a very thin film is stirred up by the eddies that arise and is practically at one temperature. In the film the heat is transferred, not by motion of the fluid, but by thermal conduction alone; and since most liquids are very bad conductors, even a thin film introduces great resistance to the heat transfer. The thickness of the non-eddy film depends upon the velocity of flow; it diminishes as the velocity increases, and there is a corresponding increase in transmission.

We can define the coefficient of transmission for the fluid on each side of the pipe wall in the same way as for the pipe itself.

|                            |                               |                               |
|----------------------------|-------------------------------|-------------------------------|
| Fluid.<br>I.<br>$t$<br>$k$ | Wall.<br>$t_1$ $t_2$<br>$k_0$ | Fluid.<br>II.<br>$t'$<br>$k'$ |
|----------------------------|-------------------------------|-------------------------------|

Calling the coefficients  $k$ ,  $k_0$  and  $k'$ , and the temperatures  $t$ ,  $t_1$ ,  $t_2$ ,  $t'$ , as shown in the figure; then, if  $H$  is heat flowing per unit time, and  $A$  is the area through which it flows.

$$\frac{H}{Ak} = t - t_1 \quad \frac{H}{Ak_0} = t_1 - t_2$$

$$\frac{H}{Ak'} = t_2 - t'$$

whence

$$\frac{H}{A} \left( \frac{1}{k} + \frac{1}{k_0} + \frac{1}{k'} \right) = t - t'$$

and  $\frac{1}{k} + \frac{1}{k_0} + \frac{1}{k'}$  is the reciprocal of the effective or over-all coefficient of transmission. If this is known, and  $t - t'$  is known, the heat transfer can be calculated. The calculation of the effective

coefficient from the separate values  $k$ ,  $k_0$ ,  $k'$  can be easily made by means of an alignment chart. (Fig. 1.) Usually (*i.e.*, for metal pipes)  $k_0$  is very large compared with  $k$  and  $k'$ , and, consequently,  $\frac{1}{k_0}$  has a negligible effect, and can therefore be left out of account altogether.

FIG. 1

## ALIGNMENT CHART FOR RESULTANT COEFFICIENT OF TRANSMISSION

$$\frac{1}{k} = \frac{1}{k_1} + \frac{1}{k_2} + \frac{b-a}{K}.$$

| To find res. coeff. of trans. |               |
|-------------------------------|---------------|
| Join Scales.                  | Intersecting. |
| A and B                       | C             |
| C and D                       | E             |

When calculations are required for much smaller coefficients the scale values on *A* and *B* can be divided by any factor such as 100. The scale value of *C* must then be divided by the same factor. Scale *D* cannot be used with these altered scales.

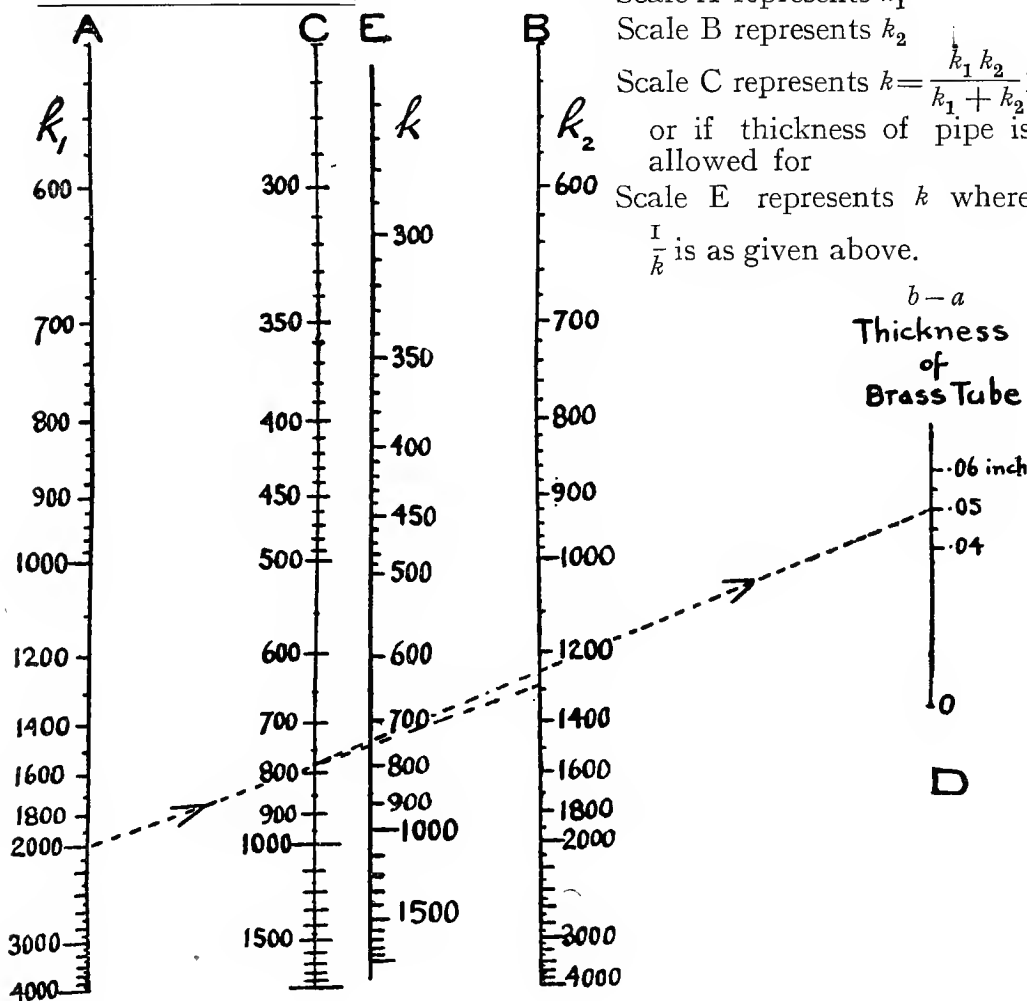
Scale A represents  $k_1$

Scale B represents  $k_2$

Scale C represents  $k = \frac{k_1 k_2}{k_1 + k_2}$ ;  
or if thickness of pipe is allowed for

Scale E represents  $k$  where  $\frac{1}{k}$  is as given above.

$\frac{b-a}{K}$   
Thickness  
of  
Brass Tube



**Criterion for Turbulence.**—When the velocity of the fluid is small enough, it moves without turbulence. In such a case  $k$  has a very small value. It was shown by Osborne Reynolds, by experiment on cylindrical tubes, that in such tubes turbulence does not begin until the velocity reaches a particular critical value depending upon the viscosity and density of the fluid and the diameter of the pipe.

The equation determining this critical velocity is—

$$v_{\text{crit}} \left( \text{in } \frac{\text{feet}}{\text{sec.}} \right) = 400 \times \frac{\text{viscosity in Brit. units (ft. lb. sec)}}{\text{specific gravity} \times \text{diameter of pipe in inches.}}$$

The viscosity varies very fast with temperature; the following tables are useful; they give the viscosity in British units.

*Water*

| Temp. | Viscosity. |
|-------|------------|
| ° C.  |            |
| 0     | ·001250    |
| 40    | ·000441    |
| 80    | 241        |
| 100   | 192        |

*Nitric Acid*

| HNO <sub>3</sub> | Viscosity at |         |
|------------------|--------------|---------|
| Per cent.        | 10° C.       | 20° C.  |
| 53·9             | 0·00198      | 0·00156 |
| 61·56            | 232          | 175     |
| 71·24            | 221          | 156     |
| 100              | 152          | 119     |

*Sulphuric Acid*

| Wt. per cent. H <sub>2</sub> SO <sub>4</sub> | Grms. H <sub>2</sub> SO <sub>4</sub> per 1,000 c.c. of Solution. | Viscosity.        |
|----------------------------------------------|------------------------------------------------------------------|-------------------|
| 3·3                                          | 33·0                                                             | 0·00712 at 20° C. |
| 11·4                                         | 114·2                                                            | 813 „             |
| 36·5                                         | 458·4                                                            | ·00155 „          |
| 52                                           | 748·3                                                            | 267 „             |
| 60                                           | 922·6                                                            | 407 „             |
| 75                                           | 1240·4                                                           | 950 „             |
| 100                                          | 1840·0                                                           | ·01454 „          |
| 100                                          | 1840·0                                                           | ·0215 at 11°·2 C. |

The viscosity of all liquids diminishes with rise in temperature. For rough purposes, when the true variation is not known, it may be taken as following an exponential law, *i.e.*, equal rises in temperature produce equal *ratios* of fall in viscosity.

**Determination of coefficient of Transmission.**—The case of non-turbulent motion in a cylindrical tube can be worked out exactly. The velocity follows the law,  $V = V_{\text{axis}} \left(1 - \frac{r^2}{a^2}\right)$  where  $a$  is the radius and  $r$  is the distance from the axis of the point whose velocity is  $V$ . The distribution of temperature across the pipe is given by the curve shown below—the ordinates being excess temperatures above that of the inside of pipe wall.

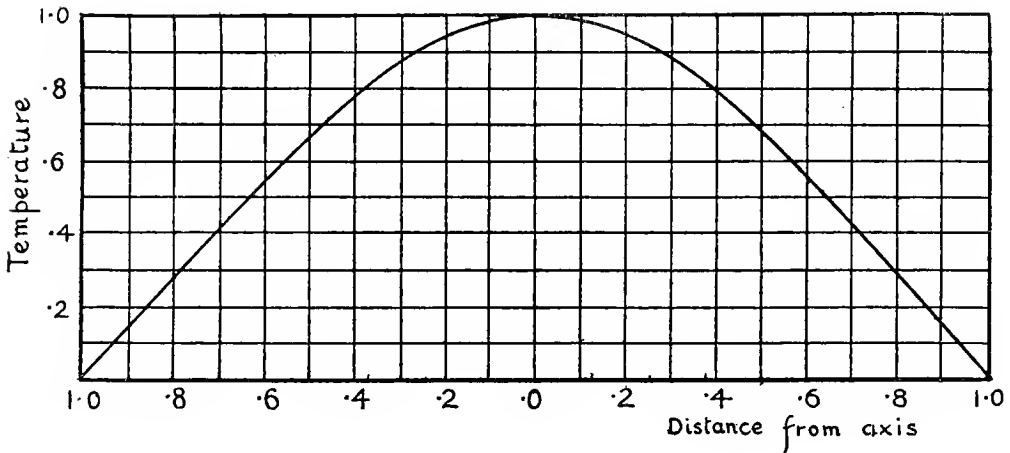


FIG. 2.

The coefficient of transmission in this case is only about 4 C.H.U./deg.C./ft.<sup>2</sup>/hour for a pipe of 1 foot inside *circumference*; for smaller pipes it is higher.

When the velocity is great enough to ensure decided turbulence, much greater coefficients are obtained, especially for gases at high pressures and velocities. Unfortunately the case of turbulent motion cannot, in general, be solved completely and recourse must be made to such experimental results as exist, together with such additional aid as can be obtained from dimensional considerations. It is still more unfortunate that the details of experiments are often so incomplete that no general law can be deduced with certainty.

The controlling factor is the non-turbulent film of flowing fluid which is in contact with the wall of the pipe. The coefficient of transmission for the fluid *on one side* of the pipe is  $K/\text{film-thickness}$ . For any given fluid, therefore, the thickness of film necessary to reduce the coefficient to any stated value can be calculated. For example, for water the following values have been calculated; in making the calculation the logarithmic formula has been used instead of the approximate one.

| Coefficient of Transmission.<br>$\kappa$ | Film thickness, in inches, for the stated value of $\kappa$ . |     |     |      |      |       |       |
|------------------------------------------|---------------------------------------------------------------|-----|-----|------|------|-------|-------|
|                                          | 5                                                             | 10  | 20  | 50   | 100  | 500   | 1000  |
| Radii of pipe in inches.                 |                                                               |     |     |      |      |       |       |
| 0.6                                      | 1.93                                                          | .61 | .26 | .092 | .045 | .0089 | .0044 |
| 1.2                                      | 1.23                                                          | .52 | .24 | .090 | .045 |       |       |
| 2.4                                      | 1.04                                                          | .47 | .23 | .089 | .043 |       |       |
| 3.6                                      | 1.01                                                          | .46 | .23 | .087 |      |       |       |
| 4.8                                      | .96                                                           | .46 | .22 | .086 |      |       |       |
| 6.0                                      | .92                                                           | .45 | .22 | .086 |      |       |       |
| 7.2                                      | .91                                                           | .45 | .22 | .086 |      |       |       |

In order that the coefficient may be 1000, the thickness must be only .0044 inch; whereas a thickness of .045 inch reduces the coefficient to 100. It will be seen, therefore, how exceedingly important this film is, and how advantageous any circumstance will be that tends to reduce its thickness.

This is also an appropriate place to point out how influential will be a thin film of any poorly conducting deposit in the pipe in regard to heat transmission. Such a deposit may easily have a thermal conductivity only of the same order as that of water, and it will form an absolutely stagnant layer. This must be well borne in mind. The data that are deduced later all refer to clean pipes of the sizes given; no general rule can be given of the amount of deposit to expect. Unless the pipes can be frequently cleaned out, or unless the process is unfavourable to the formation of a deposit, the behaviour may often be very spasmodic, owing to temporary depositions.

**Application of method of dimensions.**—In order to find the influence of the various factors concerned upon the coefficient of transmission, the only feasible way is by the method of dimensions. This method consists in utilising the fact that the fundamental physical quantities of mass,  $M$ , length,  $L$ , and time,  $T$  must enter in the same way in the case of any two quantities that can be equated one to the other. Now  $\kappa = K/\text{thickness}$ . We may assume that  $\kappa$  is proportional to  $K$ , and find how the film-thickness depends upon the physical data, viz., density,  $D$ , of fluid, viscosity,  $\mu$ , of fluid, diameter,  $d$ , of pipe, and the mean velocity of flow,  $v$ . The simplest assumption to make is that each of these enters as a power of itself, and we write—

$$\frac{1}{\text{thickness}} \text{ is proportional to } D^x \mu^y d^z v^n.$$

Now the dimensions of the several quantities are

|                                             |                 |
|---------------------------------------------|-----------------|
| thickness                                   | $L$             |
| density = $\frac{\text{mass}}{\text{vol.}}$ | $\frac{M}{L^3}$ |
| viscosity                                   | $\frac{M}{LT}$  |
| diameter                                    | $L$             |
| velocity                                    | $\frac{L}{T}$   |

Because the mass must enter to the same power on both sides of the equation

$$0 = x + y.$$

Similarly for length

$$-1 = -3x - y + z + n.$$

Similarly for time

$$0 = -y - n.$$

Hence

$$\begin{aligned} y &= -n \\ x &= n \\ z &= -1 + 3n - n - n \\ &= n - 1. \end{aligned}$$

$$\text{Thus } \frac{1}{\text{thickness}} \text{ varies as } \left( \frac{v D}{\mu} \right)^n d^{n-1}$$

and the coefficient of transmission is this multiplied into the thermal conductivity of the fluid.

This is as far as the method carries one. The value of  $n$  and the factor of proportionality require to be found by experiment.

Stanton (*Phil. Trans. A* (1897), p. 67) experimented with a copper tube, 48 cms. long, the outer diameter of which was 1.47 cms., inner diameter 1.39 cms., containing water raised throughout to  $47\frac{1}{2}^{\circ}$  C. It was surrounded by a jacket, the jacket space being 0.165 cms., containing running water. When the velocity of the water was 69 cms./sec (about 135 feet/min.) the rise of temperature was 6.47 C. This is equivalent to a coefficient of transmission of 0.061 cal./cm.<sup>2</sup>/deg.C./sec./, or 450 C.H.U./foot<sup>2</sup>/deg.C./hour.

With increased velocity the coefficient increases less fast than the velocity, *i.e.*,  $n < 1$ .

Stanton's experiments on the flow of water give  $n = 0.73$  for smooth glass pipes, and 0.86 for smooth copper, increasing to 1.0 as a limit for rough metal.

An examination of Joule's condenser experiments lead to a value about 0.75. Experiments made by Greenwood, Acland and Nobbs

give 0.71 for the case of compressed gases. It is probable that it will not be far wrong to take  $n = 0.75$ , so that

$$\kappa \text{ varies as } K \left( \frac{vD}{\mu} \right)^{\frac{1}{4}} \frac{1}{d^{\frac{1}{4}}}.$$

In the case of liquids,  $K$  may be taken as independent of temperature, so that for any particular substance its value can be included in the factor of proportionality.

This formula is represented by the accompanying alignment charts, by which the coefficient can be calculated for a wide range of conditions. Fig. 3 is where water is the flowing liquid, and Fig. 4 is for hydrogen, specially at high pressures. Factors are given on the charts to adapt them to other fluids.

The values given apply to circular pipes. If the outer fluid is in an annular space surrounding the pipe, it would seem to be fair to treat it as equivalent to a pipe of diameter equal to the difference of the diameters of its outside and inside surfaces. The value of  $\kappa'$  can then be found from the appropriate chart on this assumption, and then the over-all coefficient is given, as we have said, by

$$\text{Reciprocal of over-all coefficient} = \frac{1}{k} + \frac{1}{k'}.$$

The following tables are calculated as examples, on the assumption that the equivalent diameters, inside and out, are about the same. They can be used to estimate, roughly, the values appertaining to not very widely different circumstances from those specified.

Over-all coefficient of transmission  $\kappa$  for water expressed in C.H.U./ft.<sup>2</sup>/deg. C./hour.

*Pipe 1-in. diameter. 20° C.*

| Velocity inside.  | 100 | 200 | 300 | 400 | 500 |
|-------------------|-----|-----|-----|-----|-----|
| Velocity outside. |     |     |     |     |     |
| 100               | 160 | 185 | 224 | 240 | 251 |
| 200               | 185 | 220 | 277 | 302 | 318 |
| 300               | 224 | 277 | 375 | 421 | 454 |
| 400               | 240 | 302 | 421 | 480 | 523 |
| 500               | 251 | 318 | 454 | 523 | 570 |

*Pipe 6-in. diameter. 20° C.*

|                   |     |     |     |     |     |
|-------------------|-----|-----|-----|-----|-----|
| Velocity outside. |     |     |     |     |     |
| 100               | 97  | 123 | 137 | 146 | 152 |
| 200               | 123 | 168 | 195 | 214 | 228 |
| 300               | 137 | 195 | 232 | 250 | 280 |
| 400               | 146 | 214 | 260 | 294 | 320 |
| 500               | 152 | 228 | 280 | 320 | 352 |

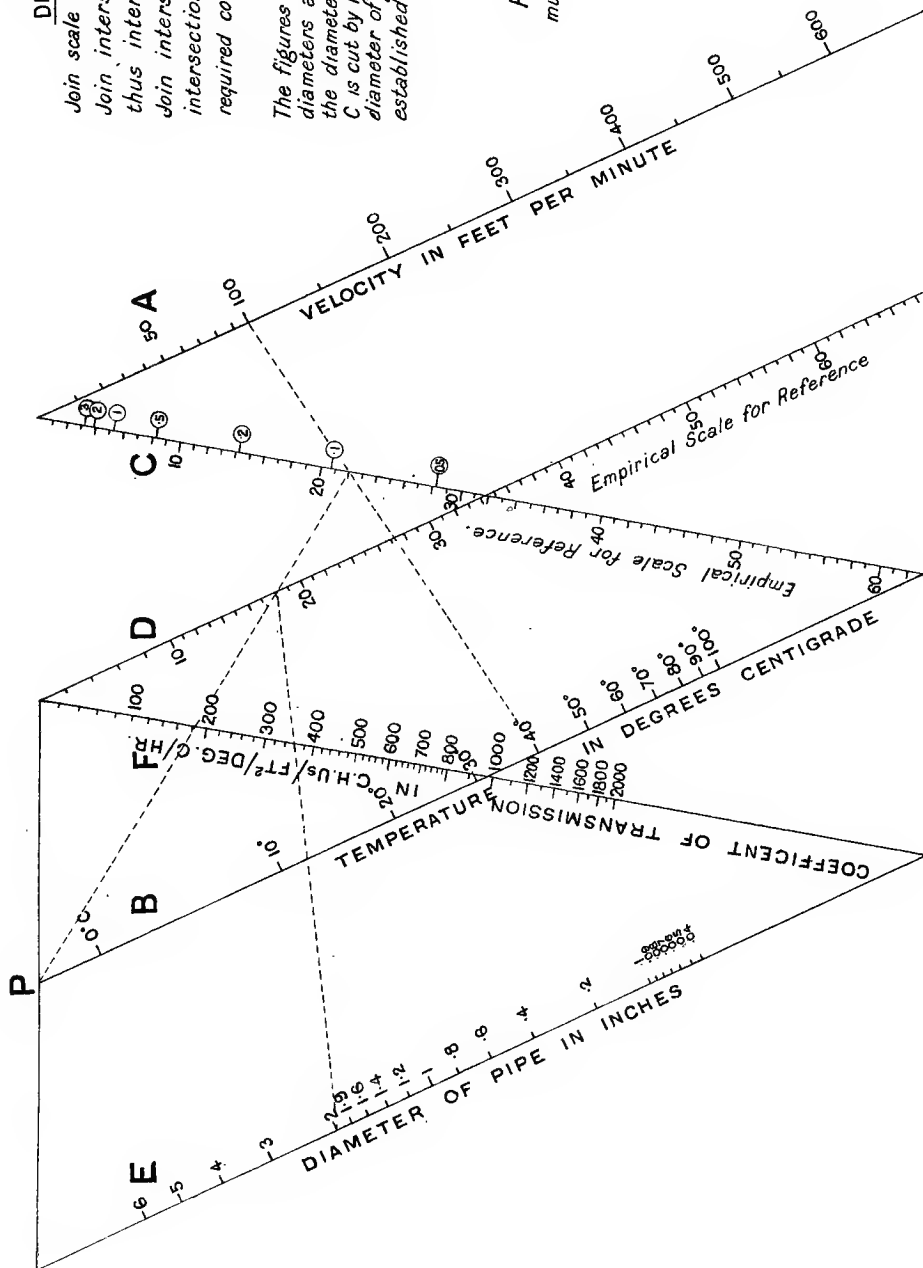
Velocities are in feet per min.

**DIRECTIONS FOR USE.**

Join scale **A** with scale **B** intersecting **C**  
Join intersection with **C** to Radiant **P**.  
thus intersecting **D**.  
Join intersection with **D** to scale **E**, the  
intersection with scale **F** gives the  
required coefficient of transmission.

The figures in circles on scale **C** denote the  
diameters above which turbulence exists. If  
the diameter corresponding to the point at which  
**C** is cut by line from **A** to **B** is less than the  
diameter of proposed pipe turbulence will be  
established in the pipe

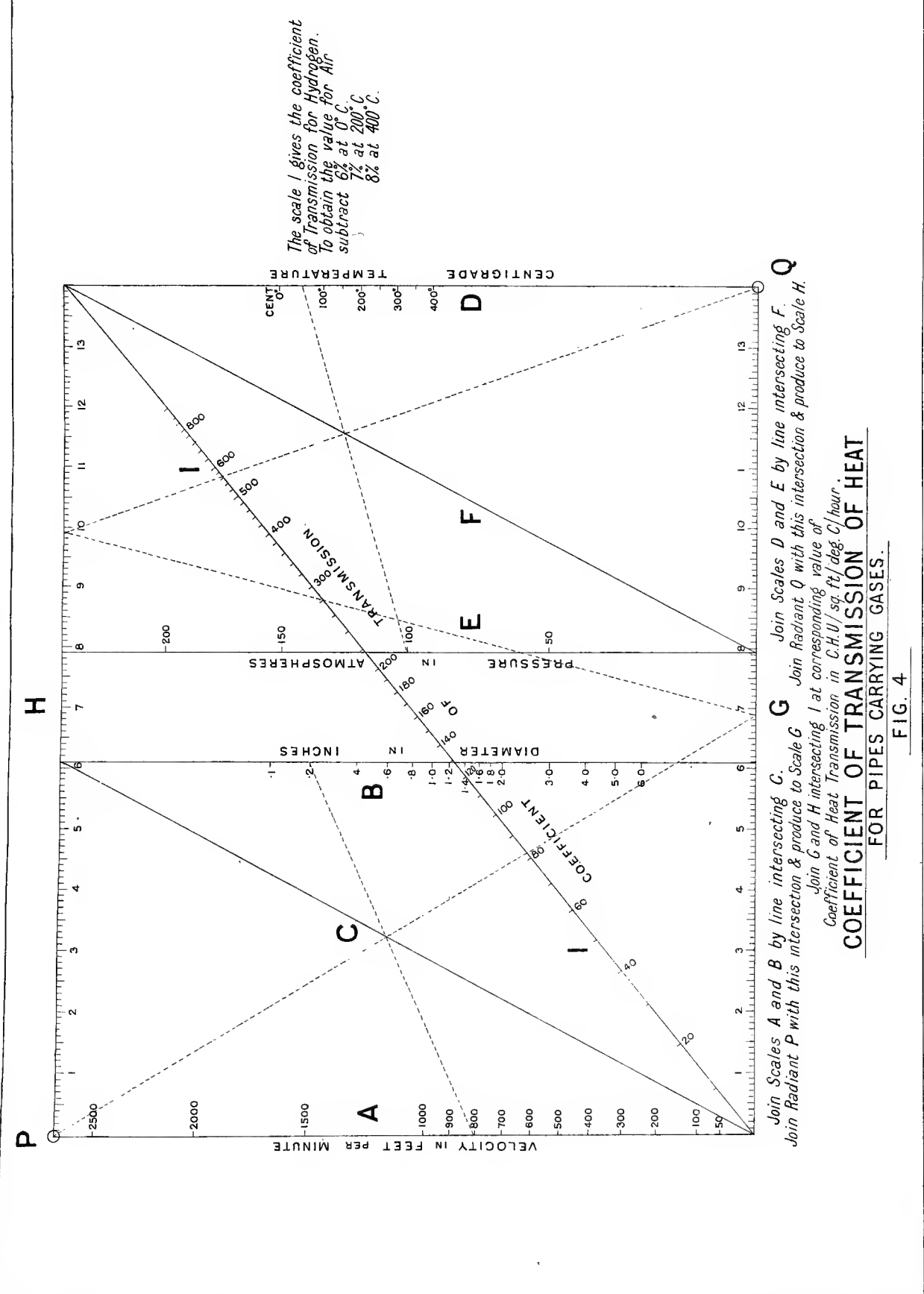
For 90%  $H_2SO_4$  at  $20^\circ C$   
multiply coefficient by 0.8



**COEFFICIENT OF TRANSMISSION OF HEAT**  
**FOR PIPES CARRYING WATER**

**FIG. 3.**





The scale I gives the coefficient of Transmission for Hydrogen. To obtain the value for Air subtract 6% at 0° C. 7% at 200° C. 8% at 400° C.

Join Scales A and B by line intersecting C. G Join Scales D and E by line intersecting F. Q  
Join Radiant P with this intersection & produce to Scale H. Join Radiant Q with this intersection & produce to Scale H.

Join G and H intersecting I at corresponding value of Coefficient of Heat Transmission in C.H.U./sq.ft./deg.C./hour.

# COEFFICIENT OF TRANSMISSION OF HEAT

FOR PIPES CARRYING GASES.

FIG. 4



All data are for perfectly clean pipes. For ordinary pipes 30–50 per cent., or even more, must be deducted to allow for incrustations.

Hausbrand's tables give values considerably different from these; but they are based on an imperfect interpretation of Joule's experiments on the surface condensation of steam, and make no allowance whatever for the influence of the size of pipe.

**Application of the coefficient of transmission to specific problems.**—There are three specific types of interchange which we will specially consider.

**TYPE I.**—A coil of pipe carrying circulating fluid is placed in a tank or vat, in which the fluid to be cooled (or warmed) is kept well agitated. We shall call this Tank interchange.

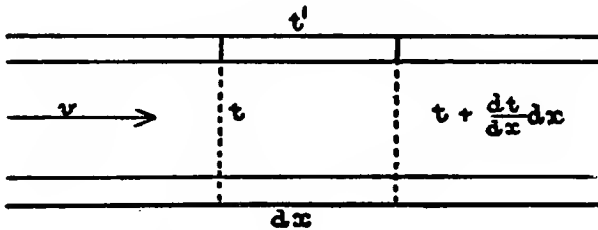
A pipe of inner radius  $a$ , and outer radius  $b$ , of overall coefficient of transmission  $C$ , carries liquid of specific heat  $c$ , density  $D$ , velocity  $v$ , entry temperature  $t_0$ , temperature at distance  $x$  along its length,  $t_1$  exit temperature after travelling a length  $l$  of pipe,  $t$ . Temperature in tank,  $t'$  (supposed uniform throughout owing to efficient stirring).

Consider a length  $dx$  of the pipe. If  $C$  be written for the *overall coefficient*, then we have seen that

$$\frac{H}{\text{Time}} = C \, 2\pi a \, (t - t'),$$

where  $H$  is the heat that flows through unit length of wall in the given time, the area of this unit length being  $2\pi a$ . The heat that is brought in by the flowing fluid in unit time is  $\pi a^2 \cdot D \cdot cvt$ , and that similarly carried out is

$$\pi a^2 Dcv \left( t + \frac{dt}{dx} dx \right).$$



The loss is  $\pi a^2 Dcv \frac{dt}{dx} dx$ , and when the steady state is attained this must equal the algebraic amount carried inwards through the length  $dx$  of wall, or

$$- C 2\pi a (t - t') dx.$$

Hence

$$\pi a^2 Dc v \frac{dt}{dx} = - C 2\pi a (t - t')$$

or

$$\frac{1}{t - t'} \frac{dt}{dx} = - \frac{2C}{aDcv}$$

which, on being integrated, gives

$$\log (t - t') = - \frac{2Cx}{aDcv} + \text{constant of integration.}$$

When  $x = 0$   $t = t_0$  whence

$$\log \frac{t - t'}{t_0 - t'} = - \frac{2Cx}{aDcv}.$$

When  $x = l$   $t = t_l$  whence

$$\log \frac{t_l - t'}{t_0 - t'} = - \frac{2Cl}{aDcv}.$$

To find the total heat transferred for a pipe of length  $l$ , we have

$$\begin{aligned} \text{Total heat per unit time} &= \int_0^l C 2\pi a (t - t') dx \\ &= \int_0^l C 2\pi a (t_0 - t') e^{\frac{-2Cx}{aDcv}} dx \\ &= \pi a^2 \cdot Dcv (t_0 - t') \left( 1 - e^{\frac{-2Cl}{aDcv}} \right). \end{aligned}$$

It is clear from this equation that the amount of heat transferred is *not proportional to the length of the pipe*. If the length of pipe is found which would transfer just half of the maximum quantity corresponding to an infinite length (viz.,  $\pi a^2 Dcv(t_0 - t')$ ), then

|                                  |   |   |                 |
|----------------------------------|---|---|-----------------|
| twice that length would transfer | - | - | $\frac{3}{4}$   |
| four times                       | " | " | $\frac{7}{8}$   |
| eight times                      | " | " | $\frac{15}{16}$ |

and so on.

It follows at once that additional lengths of pipes are not so effective as the first one. In other words, let us suppose that, in a particular installation, 20 feet of piping are found not to be sufficient—merely changing the temperature of the hot fluid from 100° to 80°, instead of to 60°, as desired. Then another 20 feet will not change the temperature through the remaining 20°, but only to 70°. A further 20 feet would change it to 65°; and so on. The explanation, of course, lies in the simple fact that the transfer per unit length is proportional to the temperature difference on the two sides of the pipe wall ( $t - t'$ ), and this gets less as the length of pipe is increased. To cool the stuff in the tank to the temperature of the water in the pipe would require an infinite length of pipe. This is impossible, and even a great length is economically wrong. It is not possible to give any general rule as to the length that should be taken. If the piping is fairly cheap and indestructible in the process for which it is used, then it will pay to put in a long length once for all, and thus gain in efficiency of transfer of heat. But if the pipe is liable to quick corrosion, the cost of replacement might easily swamp the advantage otherwise gained from increased transfer. We may introduce the term economic factor to stand for the total fraction of transferable heat (proportional to  $t_0 - t'$ ) which the



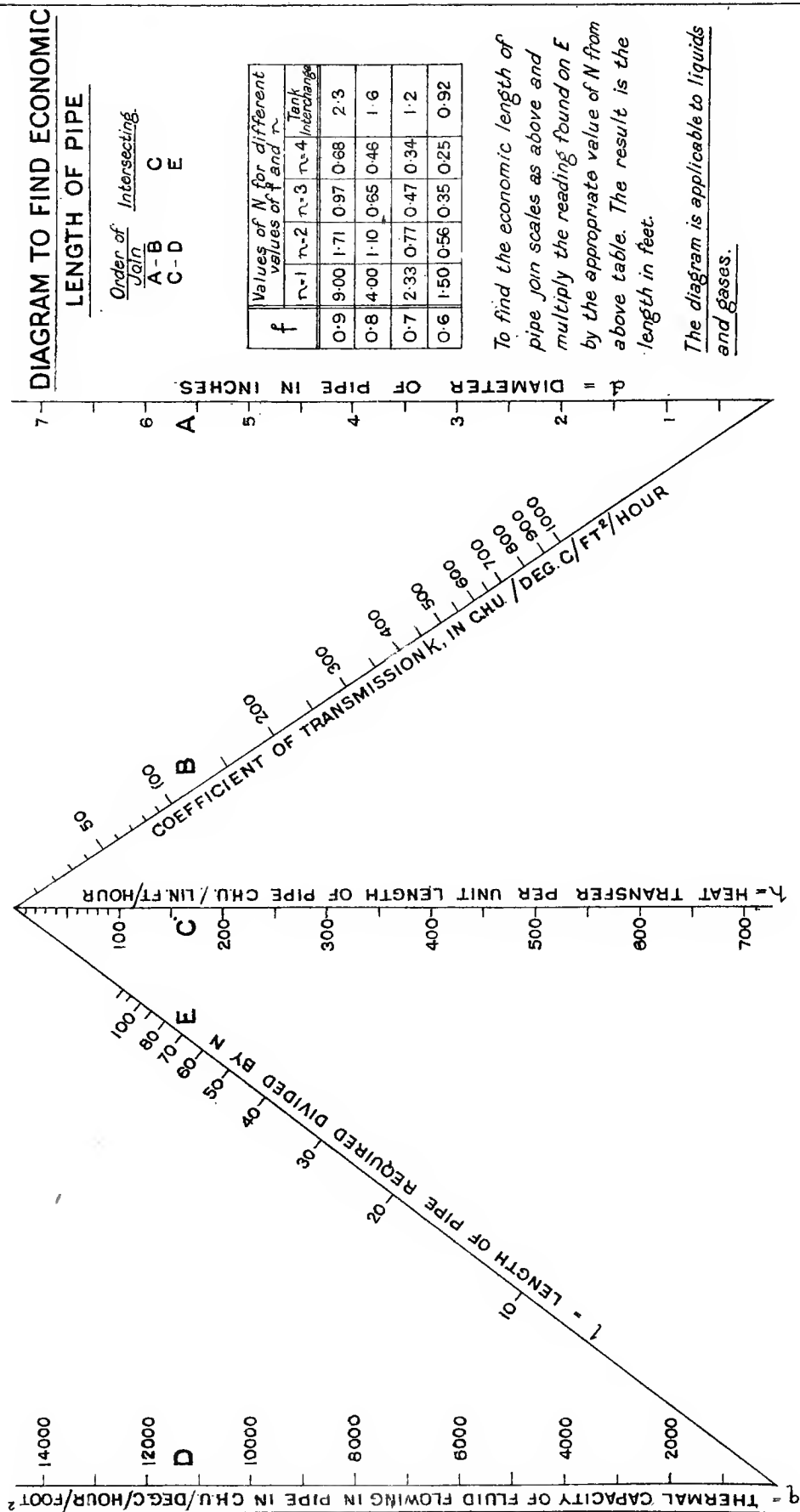


FIG. 5.

particular installation will actually transfer. This fraction, as we have seen, bears the same proportion to

$$(t_0 - t') \left( 1 - e^{-\frac{2Cl}{aDcv}} \right);$$

thus for tank interchange the economic factor  $f$  is

$$f = \left( 1 - e^{-\frac{2Cl}{aDcv}} \right).$$

**Determination of length of pipe required.**—From the last equation, if we write

$$\lambda l = \frac{2Cl}{aDcv}, \text{ it also equals } \log_e \frac{1}{1-f} \\ = N. \text{ say.}$$

The values of  $N$  for various values of  $f$  are adjoined :—

| $f$ | $N$  |
|-----|------|
| 0.9 | 2.3  |
| 0.8 | 1.6  |
| 0.7 | 1.2  |
| 0.6 | 0.92 |

Thus  $\lambda l$  is determined when  $f$  is decided upon; a value for  $f$  of 0.7 or 0.8 is usually suitable. The value of  $\lambda$  is equal to

$$\frac{\text{overall coefficient of transmission} \times \text{circumference of pipe}}{\text{thermal capacity of fluid flowing in pipe per unit time.}}$$

When these are known the value of the length of pipe required can be calculated. The calculation is most easily made by alignment charts. (Fig. 5.)

**TYPE II.—Counter-current interchange.**—We may describe this, in its simplest form, as transfer effected when the liquid to be cooled passes along a cylindrical pipe and cold liquid (which will become warmed as it flows) passes in the reverse direction through the annular space between the pipe and an outer one. In most cases this is only a description of an idealised form, but it is useful to adopt it in order to bring out as definitely as possible the fundamental laws governing transfer between two oppositely moving fluids. We shall take no account of heat that may be lost from the outside wall to the surroundings. This is a problem which is best considered separately.

|        |          |                  |                    |               |
|--------|----------|------------------|--------------------|---------------|
| $t'_0$ | Hot $t'$ | Counter flow     | $\xrightarrow{v'}$ | Cold $t'_i$   |
| $t$    | Hot $t$  | $\xleftarrow{v}$ | Flow               | Cold $t_i$    |
| $t'_0$ | Hot      | $t'$             |                    | Cold $t'_i$ . |

To find the variation of temperature along the pipe.

We measure distance from the hot end.

In the diagram we show the fluid entering the inner pipe cold, and becoming heated, but the calculations apply to the opposite case equally. As shown, the temperature  $t'$  is everywhere greater than the temperature  $t$  at the same distance from the end of the pipe.

By the same method as in Type I

$$-\pi a^2 Dcv \frac{dt}{dx} = C2\pi a(t' - t),$$

where  $C$  is the overall coefficient of transmission.

The factor  $\pi a^2 Dcv$  is the thermal capacity of the material passing any section of the inner pipe in unit time; we shall denote it by  $q$ .

Similarly, for the annular space, if the corresponding thermal capacity is  $q'$

$$-q' \frac{dt'}{dx} = C2\pi a(t' - t).$$

Solving these two equations gives

$$t' - t = (t'_0 - t_0)e^{-(n-1)\lambda x},$$

where  $n$  is written for  $q/q'$  and  $\lambda$  for  $\frac{2\pi aC}{q}$ ; thus  $\lambda$  is the heat transmitted by unit length of pipe divided by the thermal capacity per unit time flowing in pipe.

By substitution the following useful alternative forms are obtained:

$$t_0 - t = \frac{t'_0 - t_0}{n - 1} (1 - e^{-(n-1)\lambda x})$$

$$t'_0 - t' = \frac{n}{n - 1} (t'_0 - t_0) (1 - e^{-(n-1)\lambda x}).$$

The values  $t_l$  and  $t'_l$  at the cold end are obtained by putting  $x = l$ .

It will be seen that  $(t'_0 - t')/(t'_0 - t) = n$  everywhere, and, therefore, as a particular case

$$\frac{t'_0 - t'_l}{t_0 - t_l} = n.$$

This can be seen also from elementary considerations, for the ratio of the changes of temperature of the two fluids must be inversely proportional to the thermal capacities of the amounts flowing in the two spaces in equal times.

The quantity of heat transferred per unit time by the entire pipe (length,  $l$ ) is

$$\frac{H}{\text{time}} = \frac{q}{n - 1} (t'_0 - t_0) (1 - e^{-(n-1)\lambda l})$$

$$= q(t'_0 - t_l) \left( \frac{1 - e^{-(n-1)\lambda l}}{n - e^{-(n-1)\lambda l}} \right).$$

This equation is of the same general character as that obtained for Type I.

The remarks that were made about the economic factor apply, therefore, to this case also.

In the most important case for which  $n = 1$  (i.e.,  $q = q'$ )

$$\frac{H}{\text{Time}} = q(t_0' - t_i) \frac{\lambda l}{1 + \lambda l}.$$

(N.B.—A little care is necessary in obtaining this special result, as the equation for  $H$  takes an “indeterminate” form when  $n = 1$ .) It is to be noted that the exponential term has disappeared, but the general character of the variation is much the same; i.e., as  $l$  increases  $\frac{\lambda l}{1 + \lambda l}$  changes from zero up to unity as before.

This case is important, because in common practice the available waste liquor and liquor to be heated are, on the average, about equal in amount; though, of course, a great variety of cases arises.

**Determination of  $\lambda l$  for various Values of the Economic Factor ( $f$ ).—** The value of  $f$  being the fraction of the heat entering (with incoming liquid), which is actually transferred in the installation, we have

$$\frac{f}{n} = \frac{1 - e^{-(n-1)\lambda l}}{n - e^{-(n-1)\lambda l}},$$

which determines  $\lambda l$  for various values of  $f$  and  $n$ . Solving for  $\lambda l$  we get

$$\lambda l = \frac{1}{n-1} \log_e \frac{1-f/n}{1-f}.$$

The following table gives values in various cases:—

Values of  $\lambda l$  for various values of  $n$  and  $f$ .

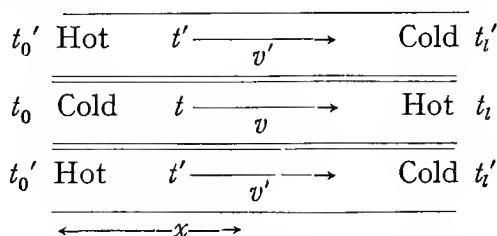
| $f$ | $n = 1$ | $n = 1.5$ | $n = 2$ | $n = 3$ |
|-----|---------|-----------|---------|---------|
| 0.9 | 9       | 2.77      | 1.71    | 0.97    |
| 0.8 | 4       | 1.69      | 1.10    | 0.65    |
| 0.7 | 2.33    | 1.15      | 0.77    | 0.47    |
| 0.6 | 1.50    | 0.81      | 0.56    | 0.36    |

The value of  $\lambda l$  is therefore determined when the permissible value of the economic factor has been fixed from experience; usually from 0.7 to 0.8 is a suitable value. The length of pipe is then calculated by dividing the number in the table by  $\lambda$ , i.e., by

$$\frac{\text{coefficient of transmission} \times \text{circumference of pipe}}{\text{thermal capacity of fluid flowing in pipe per unit time}}.$$

These calculations are made by means of the alignment charts.

TYPE III.—*Co-current (or parallel current) interchange.*—In this case the flow of both currents is in the same direction; it can be depicted graphically, thus :—



Both the fluids enter at the left and travel along the system. The temperature  $t'$  must be greater than  $t$ . The problem is to express the total flow in terms of  $t'_0$  and  $t_0$ .

Proceeding on similar lines, and putting  $\frac{q}{q'} = p$ .

$$\frac{H}{\text{time}} = \frac{q}{p + 1} (t'_0 - t_0) (1 - e^{-(p+1)\lambda l}).$$

The difference of temperature between outside and inside diminishes along the pipe according to an exponential law. The final temperature of the inside fluid is given in terms of the initial values by

$$t_i - t_0 = \frac{t'_0 - t_0}{p + 1} (1 - e^{-(p+1)\lambda l}).$$

Co-current transfer is not nearly so important as counter-current. It will not be discussed further. The discussion, in any case, would be conducted on the same lines as in the previous case.

#### CHART FOR LIQUIDS (Fig. 3.)

**Construction of Alignment Charts.**—Scale A is a uniform scale of (velocity)<sup>‡</sup>. Scale B is a uniform scale of (viscosity of water)<sup>‡</sup>. The viscosity of water depends upon the temperature. The scale is labelled, not with the numbers giving viscosities, but with the temperature C, to which the points on the scale correspond. This is done because the temperature will be the actual datum. The intersection of the support C by the line joining A to B therefore represents (vel./visc.)<sup>‡</sup> on a scale which is non-uniform. By projection from P it is translated into a uniform scale on the support D.

Scale E is a uniform scale of (diameter of pipe)<sup>‡</sup>. The intersection of the diagonal F by the join from D to E gives, therefore,

$$\left( \frac{\text{vel.}}{\text{visc.}} \right)^{\frac{1}{2}} \frac{1}{(\text{diam})^{\frac{1}{2}}}$$

which is proportional to the coefficient of transmission. The support F is so labelled.

Both the thermal conductivity and density of water are taken as constant. This is a near-enough approximation in practice.

The absolute values of the coefficient marked on support *F* have been chosen to suit experimental data. The values of the viscosity of water which have been made use of are given below.

| Temperature C. | Viscosity of Water. |                     |
|----------------|---------------------|---------------------|
|                | C.G.S. units.       | Ft. lb. sec. units. |
| 0              | 0.01793             | 0.0012              |
| 10             | 1311                | 0.00082             |
| 20             | 1006                | 67                  |
| 30             | 800                 | 53                  |
| 40             | 657                 | 51                  |
| 50             | 550                 | 37                  |
| 60             | 469                 | 31                  |
| 70             | 406                 | 27                  |
| 80             | 356                 | 24                  |
| 90             | 316                 | 21                  |
| 100            | 284                 | 18                  |

Directions for using the chart are given upon it. It is to be used successively to determine the coefficient for *each* side of the pipe, the appropriate data being utilised (see p. 8). The over-all coefficient is then to be obtained by the relation already given

$$\frac{1}{\text{over-all coefficient}} = \frac{1}{\kappa} + \frac{1}{\kappa'}$$

The value of  $\kappa$  for the material of the pipe-wall is here omitted from the expression because, in practice, it makes a negligible contribution.

#### CHARTS FOR GASES (Fig. 4.)

Scale *A* is a uniform scale of (velocity)<sup>3</sup>.

Scale *B* is a uniform scale of (diameter)<sup>3</sup>.

Scale *D* is a uniform scale of

$$\text{Therm. cond. of gas at } t^{\circ} \text{ C.} \times \left[ \frac{\text{viscosity at } t^{\circ} \text{ C.}}{\text{density at } t^{\circ} \text{ and 1 Atm.}} \right]^{\frac{1}{3}}$$

The numbers labelling this scale are the temperatures to which the points on the scale correspond.

Scale *E* is a uniform scale of (pressure of gas)<sup>3</sup>.

The intersection of *C* by the line joining *A* and *B* gives (vel.)<sup>3</sup>/(diam.)<sup>3</sup>. By projection from *P* its scale is translated into a uniform scale on support *G*.

The intersection of *F* by the line joining *D* to *E* gives (press.  $\times$  dens. at 1 Atm.)<sup>3</sup>/(viscosity)<sup>3</sup>.

By projection from *Q* its scale is translated into a uniform inverse scale on *H*.

The temperature varies along the length of the pipe and the coefficient of transmission varies with it. The problem becomes intractable if this variation is taken into account. It is necessary to take a mean value of the temperature as giving a mean value of the coefficient. The mean value may often be taken as the arithmetic mean of the extreme values; it is more nearly  $(t_0 - t_e)/\log_e (t_0/t_e)$ .

Since  $G$  and  $H$  are parallel scales, the diagonal scale  $I$  represents the ratio  $G/H$  or

$$\left[ \frac{\text{press.} \times \text{dens. at 1 atm.} \times \text{vel.}^{\frac{1}{2}}}{\text{viscosity}} \right] \times \frac{1}{(\text{diam.})^{\frac{1}{2}}}$$

which is proportional to the coefficient of transmission.

Directions for using the chart are given upon it. It is to be used successively to determine the coefficient for *each* side of the pipe, the appropriate data being used. The over-all coefficient is then to be obtained by the relation already given

$$\frac{1}{\text{over-all coefficient}} = \frac{1}{\kappa} + \frac{1}{\kappa'}$$

The value of the coefficient for the material of the pipe-wall is here omitted from the expression because, in practice, it makes a negligible contribution to the value of the over-all coefficient.

When the pipe has gas flowing on one side, and water on the other, the coefficients for the two sides must be obtained from the gas chart and water charts respectively. When the gas is a condensable gas, like steam (as in steam condensers), the question is very much complicated by the amount of condensation which occurs and the chart must not be used for such cases.

### EXPERIMENTAL SECTION

The large number of coolers actually in use in various factories provided the means of ascertaining what the efficiency of different forms is in actual practice. A number of data is given in the accompanying tables (Figs. 6 and 7). Although these tables do not contain full particulars, yet they may be taken as showing the kind of efficiency that is obtainable in practice.

Extensive investigations were made at Gretna on an acid cooler, in which water flowing over the pipes cools their contents by evaporation. This is quite a distinct problem from those heretofore described. The cooler was used in connection with a mixer, which was employed to break down oleum, or 98 per cent. sulphuric acid, to make feed acid for a Grillo plant. The mixer consisted of a pottery-lined iron cylinder, set about 10 feet above the ground, into which oleum, or 98 per cent. acid and water, are fed simultaneously in the proportions necessary to form the acid required. This acid was then fed into the cooler proper through a  $2\frac{1}{2}$  in. pipe.

FIG. 6.

H.M. Factory.

HEAT EXCHANGERS AND COOLERS *Queen's Ferry.*

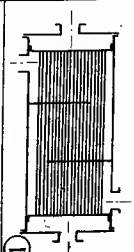
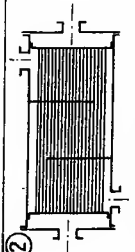
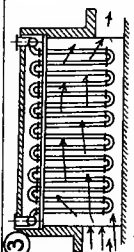
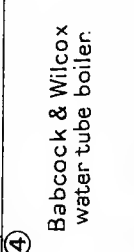
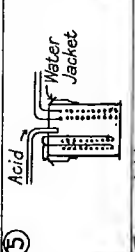
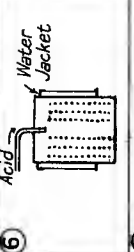
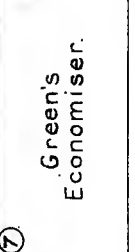
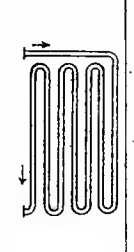
| Plant.       | Heat Exchanger.              | Material.          | Surface, Sq. ft.                                                   | Temperature Range of Cooled Substance. | Temperature Range of Cooling Medium. | Cooling Medium.     | Water Consumption, Tons per hour.                 | Mean Temperature Gradient. | Cooling Capacity in C.H.U. Sq.ft./hr. | Cooling Capacity in C.H.U.s Sq.ft./hr./ 1° C. temperature difference. |
|--------------|------------------------------|--------------------|--------------------------------------------------------------------|----------------------------------------|--------------------------------------|---------------------|---------------------------------------------------|----------------------------|---------------------------------------|-----------------------------------------------------------------------|
| Mixers       | 10 ft. x 5 ft. mixer.        | M.S.               | 316                                                                | ° C.<br>42·5-41                        | ° C.<br>6                            | Air                 | —                                                 | ° C.<br>35·7               | 68·9                                  | 1·9                                                                   |
|              | Coils<br>"                   | Lead<br>M.S.       | 70 per coil<br>80 per coil                                         | 42-30<br>42-30                         | 11<br>19                             | Water<br>"          | 3·2<br>1·7                                        | 34·0<br>34·0               | 1120·0<br>880·0                       | 33·0<br>25·9                                                          |
| Denitrators. | Outer D.N.A. cooler.         | Lead               | 78·3                                                               | 150-68                                 | 15-45                                | Water               | 3·33                                              | 94                         | 3,064                                 | 37·3                                                                  |
|              | Inner D.N.A. cooler.         | "                  | 78·3                                                               | 68-40                                  | 15-30                                | "                   | 3·33                                              | 39                         | 2,090                                 | 74·0                                                                  |
|              | D.N.A. Launder, half-full.   | "                  | $\frac{224·6}{2}$                                                  | 60-52                                  | 18-20                                | "                   | 8·33                                              | 41                         | 2·870                                 | 2·109                                                                 |
|              | Harts Condensers, 3 headers. | Glass              | 166                                                                | 110-55                                 | 15-43                                | "                   | 1·0                                               | 68                         | 702                                   | 13                                                                    |
|              | Hart's Acid Cooler.          | Narki              | 77·0                                                               | 80-35                                  | 15-27                                | "                   | 1·25                                              | 43                         | 540                                   | 12                                                                    |
|              | D.N.A.                       | Lead               | 928 including surface of liquid.                                   | 50-40                                  | 15 (air)                             | Air                 | —                                                 | 35                         | 52                                    | 10                                                                    |
|              | Pre-heating coils.           | "                  | 245                                                                | 15-60                                  | 200-60                               | Steam               | 23·7 tons H <sub>2</sub> O at 35° C. in 24 hours. | —                          | 4,860                                 | —                                                                     |
| N.C. Stills. | Coils Still                  | Silica C.I.        | 38·9<br>143·0                                                      | 117-20<br>—                            | —<br>—                               | Water<br>Air        | —<br>—                                            | 91<br>—                    | 3,473<br>—                            | 38·2<br>—                                                             |
|              | Launder                      | Lead               | 74 water and 82 air-cooled                                         | 185-112                                | 28-52                                | Air and water.      | 8·0                                               | 110                        | 5,820 10% allowed for radiation.      | 53                                                                    |
| Mannheim.    | Mixer 1 and 2 oxide coolers. | C.I.<br>M.S.       | 229<br>375                                                         | —<br>365-159                           | —<br>—                               | Water<br>"          | —<br>—                                            | —<br>—                     | —<br>513                              | —<br>—                                                                |
|              | 3 oxide cooler.              | "                  | 187                                                                | 159-65                                 | —                                    | "                   | —                                                 | —                          | 471                                   | —                                                                     |
|              | Pt. cooler                   | "                  | 187                                                                | 230-80                                 | —                                    | "                   | —                                                 | —                          | 722                                   | —                                                                     |
|              | Heat exchange.               | "                  | 495                                                                | 480-230                                | 15-240                               | SO <sub>2</sub> &c. | —                                                 | 165                        | 400                                   | 2·4                                                                   |
|              | Superheater                  | "                  | —                                                                  | —                                      | —                                    | —                   | —                                                 | —                          | —                                     | —                                                                     |
| Retorts      | Retort Hart's condenser.     | C.I.<br>Glass      | 14·3<br>202                                                        | —<br>—                                 | —<br>—                               | Air<br>Water        | —<br>—                                            | —<br>—                     | —<br>420-600                          | —<br>—                                                                |
|              | N.A. cooler                  | Pb.                | 34·6                                                               | 80-12                                  | 10-30                                | "                   | —                                                 | —                          | —                                     | —                                                                     |
| Gaillards    | Main tower cooler.           | C.I.<br>Pb. coils. | Coils, 107·7<br>C.I. water, 33·4<br>C.I. air, 15·5<br>Surface, 9·2 | 210-30                                 | 8-35                                 | Water               | 7·0                                               | 100                        | 2,850                                 | 28·5                                                                  |
|              | Recuperator cooler.          | Pb.                | 157·8                                                              | 130-45                                 | 8-25                                 | "                   | —                                                 | 60                         | —                                     | —                                                                     |
| Gilchrist    | Cooler                       | Pb.                | 153·5                                                              | 250-27                                 | 8-35                                 | Water               | 6·7                                               | 115                        | 2,637                                 | 22·9                                                                  |



# HEAT EXCHANGERS AND COOLERS.

Oct. 1917.

To follow Fig. 6 facing p.16.

| TYPE.                                                                                   | LIQUID OR GAS OUTSIDE OF TUBES. | LIQUID OR GAS INSIDE OF TUBES.  | MATERIAL OF TUBES.    | MEAN TEMPERATURE DIFFERENCE | C.H.U.s PER DEGREE DIFF. IN TEMP. PER SQ.FT. PER HR.                  | TEMP. OF HOTTER GAS OR LIQUID ENTERING AND LEAVING | TEMP. OF COLDER GAS OR LIQUID ENTERING AND LEAVING | HEATING SURFACE IN SQ. FEET | DIAMETER AND LENGTH OF PIPE                                 | RECORDS FROM                                                   | REMARKS.                                                                                                                     |
|-----------------------------------------------------------------------------------------|---------------------------------|---------------------------------|-----------------------|-----------------------------|-----------------------------------------------------------------------|----------------------------------------------------|----------------------------------------------------|-----------------------------|-------------------------------------------------------------|----------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------|
| ①    | $SO_3 +$<br>air<br>(5% $SO_3$ ) | $SO_2 +$<br>air<br>(5% $SO_2$ ) | Mild steel            | 250°c.                      | 4.16                                                                  | 414°c.<br>282°c.                                   | 14°c.<br>183°c.                                    | 600                         | 104 = 2 1/2" dia.<br>pipes in parallel.                     | Grillo Oleum plant at Greenwich                                | 70 lbs. charge of Sulphur<br>Mean gas velocity in pipes 19.25 ft. per sec.                                                   |
| ②    | Air                             | Water                           | Brass                 | 7°c.                        | 3.5                                                                   | 29°c.<br>18°c.                                     |                                                    |                             |                                                             | Based on 1 sq. ft. of surface per 5 1/2 cub. feet of free air. |                                                                                                                              |
| ③    | $SO_2 +$<br>air<br>(5% $SO_2$ ) | $SO_2 +$<br>air<br>(5% $SO_2$ ) | Cast Iron             | 178°c.                      | 3.0 or 3.4 with M.T.D. = $\frac{T_1 - T_2}{\log_e \frac{T_1}{T_2}}$   | 580°c.<br>265°c.                                   | 170°c.<br>320°c.                                   | 1020                        | 6 Rows of 8 U tubes 5" dia. 980' 0" not all heating surface | Grillo Oleum plant at Greenwich                                | 70 lbs. charge of Sulphur<br>Mean gas velocity in pipes 115 ft. per sec.                                                     |
| ④    | Furnace Gas.                    | Steam                           | Wrot Iron             | 540°c.                      | 2.0                                                                   |                                                    |                                                    |                             |                                                             |                                                                |                                                                                                                              |
| ⑤    | 72% $H_2SO_4$                   | Water                           | Lead                  | 78°c.                       | 1st cooler 64.5 2nd " 48.0 Two coolers 39.5                           | 145°c.<br>44°c.                                    | Two coolers 120°c. 120°c. 45°c. 34°c.              | 116 including water jacket  | 1 1/2" pipe 1 coil 53' 0" 1 " 71' 0" in each cooler         | Queensferry Denitration                                        | Two coolers were run with acid in series but fresh water to each cooler.<br>Mean water velocity in coils 2.28 ft. per sec.   |
| ⑥   | 91% $H_2SO_4$                   | Water                           | Lead                  | 82°c.                       | 18.4 or 28.5 with M.T.D. = $\frac{T_1 - T_2}{\log_e \frac{T_1}{T_2}}$ | 166°c.<br>16°c.                                    | 5.5°c. 13.0°c.                                     | 121 including water jacket  | 1" pipe 317' 6"                                             | Queensferry Gaillard Towers                                    | Note high range of acid temperature when considering the C.H.U.s transmitted.<br>Mean water velocity in coils 4 ft. per sec. |
| ⑦  | Furnace Gas                     | Water                           | Cast Iron             | 180°                        | 2.25                                                                  | 357°c.<br>221°c.                                   | 45°c.<br>138°c.                                    | 1440                        |                                                             |                                                                |                                                                                                                              |
|    | Water Spray                     | 20% Oleum                       | M.S. Pipes C.S. Bends | 30.5°c.                     | 22.                                                                   | 64°c.<br>42°c.                                     | 15°c.<br>30°c.                                     | 112                         | 5" dia 85' 9"                                               | Greenwich Oleum Cooler                                         | Preliminary Test.                                                                                                            |



The cooler consisted of 48 cast-iron pipes, each 9 feet long and 6 inches internal and  $7\frac{1}{2}$  inches external diameter, with 22 semi-circular bends of the same piping; it was divided into two half-coolers of 24 pipes and 11 bends each. These pipes were stacked horizontally in six layers one over the other.

The hot acid entered the first half at the top, passed forward along two pipes, turned a semi-circular bend and returned through two more pipes at the same level. It then descended, by a bend placed vertically, to the next lower level, where it flowed forward and back as before; and so on, for the six levels in all.

From the first half to the second the acid passed by a  $2\frac{1}{2}$  in. pipe, entered the second half at the bottom, and rose in it to the outlet at the top. Except that the acid flows in opposite directions (*i.e.*, up instead of down) the two halves are identical.

The pipes in each half-cooler at the different levels were below one another so that each half-cooler may be regarded as consisting of two columns of horizontal pipes, the acid passing from one to the other alternately. There were thus four columns of pipes in all, and at the top were set the perforated pipes for the delivery of the cooling water.

This arrangement means that, in the first half-cooler, water and acid were both moving downwards (parallel current cooling), while in the second the acid moved upwards against the water (counter current cooling).

To minimise splashing, pitch pine boards were placed between the pipes so as to conduct the water from one pipe to the next below.

The cooled acid was delivered from the cooler to the receiver by a  $2\frac{1}{2}$  in. pipe and thence pumped to storage.

In the actual working it was found that mixture was generally incomplete in the mixer, and, in consequence, in the early parts of the cooler the fall of temperature was less than it would otherwise have been, or even a rise of temperature took place.

This incomplete mixing had the advantage that it avoided the development of the maximum temperature in the mixer, and so tended to preserve the plant, but it seriously hampered the experimental investigation of the performance of the cooler.

**Method of Investigation.**—Thermometer pockets were let into the cooler near the entrance and at the 12 horizontal bends. During runs these pockets were filled with oil, to obtain conducting contact between thermometers and acid. They were numbered, *A* for the one near the inlet, and 1–12 for the rest in the direction of flow of the acid, *i.e.*, downwards in the first half-cooler and upwards in the second.

Two series of investigations were carried out.

**First Series.**—The readings were practically all taken every half-hour, and fell into four main divisions.

(a) Readings of the water consumed were made by a water-meter registering gallons, installed in a water supply main.

(b) The temperatures at the 13 thermometers let into the pockets in the cooler were taken every half-hour.

(c) The temperature of the cooling water was taken just before reaching, and just after passing, each pipe (after the first 3 runs). This set of readings was less reliable than (b), for it could only be made by allowing the water to trickle over the thermometer bulb instead of completely immersing it. Fair agreement, however, was obtained.

(d) The depth of acid in the receiver was read every half-hour.

A steady state, as regards temperature in the thermometer pockets, was reached in about three hours after starting up, and variations of flow in the water were slight.

In all, ten runs were made, four using 98 per cent. sulphuric acid and six using oleum.

Some details of the runs are given herewith :—

#### *A.—Runs using 98 per cent. acid*

*Runs 1 and 2.*—Here the makes were high, and it was found possible to cool efficiently with only three-fourths of the cooler pipe water-cooled.

*Run 3.*—In this run the make was again large, and cooling was attempted with only the first half-cooler wet.

*Run 4.*—The make in this case was less, and the first half of the cooler was run dry.

#### *B.—Runs with oleum mixture*

*Run 5.*—Here the make was only moderate, and cooling was sufficient with only the first half of the cooler wet.

*Run 6.*—A run with small make. Cooling was efficient with only the first quarter of the cooler wet.

*Run 7.*—The make here was heavy, and the first half of the cooler was dry, as in No. 4 above. In this case the irregularity of the first temperatures showed very plainly.

*Runs 8, 9 and 10.*—These showed the cooler working with large feeds at high temperature. The acid feeds were practically constant, and the effect of water feed was tested by increasing it for Run 9 and again for Run 10.

## PRELIMINARY MEASUREMENTS AND DATA

| Thermometers. | Distance from<br>inlet. |                                        |
|---------------|-------------------------|----------------------------------------|
|               | Feet                    |                                        |
| A             | 0.7                     |                                        |
| 1             | 18                      |                                        |
| 2             | 54                      | Length of single pipe, 9 ft.           |
| 3             | 90                      | Internal diameter, 6 ins.              |
| 4             | 126                     | External diameter, $7\frac{1}{2}$ ins. |
| 5             | 162                     | Specific heat of mixed acid, 0.345.    |
| 6             | 198                     |                                        |
| 7             | 234                     |                                        |
| 8             | 270                     |                                        |
| 9             | 306                     |                                        |
| 10            | 342                     |                                        |
| 11            | 378                     |                                        |
| 12            | 414                     |                                        |
| Exit          | 432                     |                                        |

*First half of cooler—parallel currents*

| Run. | Temperatures. |       |       |       |      |      |      |        |    |    |    |    |    |      | Acid.          |                | Water flow.    |                   |
|------|---------------|-------|-------|-------|------|------|------|--------|----|----|----|----|----|------|----------------|----------------|----------------|-------------------|
|      | Acid.         |       |       |       |      |      |      | Water. |    |    |    |    |    |      | Tons per hour. | Heat capacity. | Tons per hour. | Gallons per hour. |
|      | A             | 1     | 2     | 3     | 4    | 5    | 6    | 1      | 2  | 3  | 4  | 5  | 6  | Mean |                |                |                |                   |
| 1    | 67.0          | 62.5  | 53.0  | 47.0  | 43.5 | 40.5 | 38.5 | —      | —  | —  | —  | —  | —  | —    | 6.66           | 5150           | 2.24           | 500               |
| 2    | 75.0          | 69.5  | 58.5  | 51.5  | 48.5 | 45.0 | 42.0 | —      | —  | —  | —  | —  | —  | —    | 5.08           | 3930           | 1.96           | 440               |
| 3    | 79.0          | 71.0  | 60.0  | 52.5  | 48.5 | 45.0 | 42.5 | —      | —  | —  | —  | —  | —  | —    | 5.06           | 3920           | 2.18           | 490               |
| 5    | 139.0         | 131.0 | 101.0 | 76.0  | 65.5 | 55.5 | 49.5 | 19     | 37 | 45 | 43 | 40 | 37 | —    | 3.02           | 2330           | 1.51           | 340               |
| 8    | 131.5         | 102.5 | 88.0  | 108.5 | 95.0 | 82.5 | 74.0 | 20     | 47 | 52 | 47 | 41 | 39 | —    | 4.90           | 3780           | 1.58           | 355               |
| 9    | 130.0         | 100.0 | 85.5  | 106.5 | 90.5 | 79.0 | 71.0 | 20     | 45 | 44 | 45 | 48 | 46 | —    | 4.68           | 3620           | 2.11           | 475               |
| 10   | 120.0         | 102.0 | 86.0  | 105.0 | 88.5 | 76.5 | 69.0 | 19     | 42 | 45 | 47 | 41 | 46 | —    | 4.59           | 3550           | 2.78           | 625               |

*Second half of cooler—counter-current flow*

| Run. | Temperatures. |      |      |      |      |      |        |    |    |    |    |    |      | Acid make.     |                       | Water flow.    |                   |
|------|---------------|------|------|------|------|------|--------|----|----|----|----|----|------|----------------|-----------------------|----------------|-------------------|
|      | Acid.         |      |      |      |      |      | Water. |    |    |    |    |    |      | Tons per hour. | Heat capacity. C.H.U. | Tons per hour. | Gallons per hour. |
|      | 7             | 8    | 9    | 10   | 11   | 12   | 7      | 8  | 9  | 10 | 11 | 12 | Mean |                |                       |                |                   |
| 4    | 47.5          | 42.5 | 39.5 | 37.5 | 34.0 | 32.0 | 26     | 24 | 23 | 20 | 19 | 18 | 23   | 4.20           | 3270                  | .96            | 215               |
| 7    | 112.0         | 90.5 | 84.0 | 77.5 | 68.5 | 61.0 | 28     | 27 | 25 | 23 | 21 | 19 | 35   | 5.48           | 4270                  | 1.69           | 380               |
| 8    | 66.5          | 56.5 | 53.5 | 49.5 | 45.0 | 41.0 | 45     | 40 | 33 | 29 | 21 | 18 | 27   | 4.90           | 3780                  | 1.58           | 355               |
| 9    | 64.0          | 53.5 | 50.0 | 45.5 | 41.0 | 37.5 | 32     | 27 | 27 | 24 | 21 | 20 | 25.5 | 4.68           | 3620                  | 2.11           | 475               |
| 10   | 62.0          | 51.0 | 47.5 | 43.5 | 38.5 | 35.5 | 30     | 27 | 24 | 23 | 21 | 20 | 25.5 | 4.59           | 3550                  | 2.78           | 625               |

*Air cooling*

| No. of Run. | Acid Temperatures. |   |       |      |      |      |       |      |      |      |      |      | Temperature of Air. | Acid make.     |                        |
|-------------|--------------------|---|-------|------|------|------|-------|------|------|------|------|------|---------------------|----------------|------------------------|
|             | A                  | 1 | 2     | 3    | 4    | 5    | 6     | 7    | 8    | 9    | 10   | 11   | 12                  | Tons per hour. | Therma capacity C.H.U. |
| 4           | 61                 | — | 58.5  | 56.0 | 54.5 | 52.0 | 51.0  | —    | —    | —    | —    | —    | 20                  | 4.20           | 3270                   |
| 7           | 136                | — | 141.0 | 137  | 132  | 127  | 124.5 | —    | —    | —    | —    | —    | 21                  | 5.48           | 4270                   |
| 3           | —                  | — | —     | —    | —    | —    | —     | 40.5 | 39.0 | 37.5 | 37.0 | 35.5 | 34.5                | 17.5           | 5.06                   |
| 5           | —                  | — | —     | —    | —    | —    | —     | 44.0 | 42.0 | 41.0 | 39.5 | 38.5 | 37.0                | 18.5           | 3.02                   |
| 6           | —                  | — | —     | —    | —    | —    | —     | 28.0 | 25.0 | 23.0 | 21.0 | 20.0 | 19.0                | 16.0           | 1.32                   |

**Examination of Experimental Results.**—When the above data are examined it is found that the temperatures satisfy an equation of the form given above for tank interchange (p. 9), equivalent to

$$t - t' = (t_0 - t') e^{-\text{const.} y}$$

excepting near the inlet, where, as has been said, evidences of rise of temperature, due to intermingling of acid and water, is still progressing. If the pipe is treated as conducting the heat, and if no complication, due to films of liquid on its surface, came into play, the equation for the change of temperature would be

$$t - t' = (t_0 - t') \exp. \left[ 2\pi Ky / q \log_e \frac{b}{a} \right]$$

If  $K$  be calculated from the observations it comes out considerably smaller than the value for cast iron, the calculated ratio being  $\frac{1}{2}$  for parallel current working and  $\frac{1}{4}$  for counter current working. No physical interpretation of these factors can be made, however, because when the presence of the conducting films of liquid is recognised, there

is no justification for the value of  $K$  being sensibly influenced by the conductivity of the pipe wall. The quantity to be calculated is the coefficient of transmission  $C$ . The following values have been calculated from the thermal data.

| No. of Run. | No. of Thermometer. | Temperature. | Water.         | Acid Make.     | Heat transferred per ton water. | Length of Cooler. | Type of Cooling. | Coefficient of transmission. |
|-------------|---------------------|--------------|----------------|----------------|---------------------------------|-------------------|------------------|------------------------------|
|             |                     |              | Tons per hour. | Tons per hour. | C.H.U.                          | Feet.             |                  |                              |
| 1           | 3                   | 47           |                |                |                                 |                   |                  |                              |
|             | 6                   | 38.5         | 2.24           | 6.66           | 19,200                          | 108               | Parallel         | —                            |
| 4           | 7                   | 47.5         |                |                |                                 |                   |                  |                              |
|             | 9                   | 39.5         | .96            | 4.20           | 27,200                          | 72                | Counter          | 17                           |
| 2           | 1                   | 69.5         |                |                |                                 |                   |                  |                              |
|             | 6                   | 42.0         | 1.96           | 5.08           | 55,000                          | 180               | Parallel         | —                            |
| 3           | 7                   | 66.5         |                |                |                                 |                   |                  |                              |
|             | 12                  | 41.0         | 1.58           | 4.90           | 61,000                          | 180               | Counter          | 11.3                         |
| 8           | 3                   | 108.5        |                |                |                                 |                   |                  |                              |
|             | 6                   | 74           | 1.58           | 4.90           | 82,500                          | 108               | Parallel         | 13.1                         |
| 7           | 7                   | 112          |                |                |                                 |                   |                  |                              |
|             | 10                  | 77.5         | 1.59           | 5.48           | 87,000                          | 108               | Counter          | 15.2                         |

It will be seen that the coefficient of transmission is of the same order for the case of parallel working (for which there are sufficient data) as for that of counter currents. With regard to the variation between the coefficient for different cases, it must be remembered that the conditions of working in different runs (rate of flow of liquids, temperatures, &c.) are themselves different, and, consequently, a variation was to be expected. It was at first thought to be possible to express the effect arising from the quantity of flow of water by an exponential formula; but this conclusion was afterwards withdrawn on the evidence of the Second Series of experiments, now to be described.

**Second Series.** — In this second investigation 20 new runs were carried out. A readjustment of the feed pipes to the mixing pots provided for complete mixing before the acid reached the cooler proper, and thus the maximum acid temperature was always attained at the entrance to the cooler.

Two modifications of procedure were introduced. In any one run readings were confined to one half-cooler, and so the numbering is simplified. To obtain the water temperatures, holes inclined at  $45^\circ$  and large enough to take the thermometer bulbs easily, were drilled in the splash boards between the pipes and their upper ends were gouged out upwards to bring an increased flow of water over the bulbs. A

thermometer was put in each hole and left throughout the run. This method was successful except in a few cases, for which the water fell clear of the boards altogether.

In the second half-cooler  $t'$  was related to  $t_0$  (that is the value at the inlet) by the equation

$$t' = \frac{1}{2}t_0 - 10.$$

This relation is empirical merely and was found from the experimental values; this is applicable from  $t_0 = 50^\circ$  to  $t_0 = 90^\circ$ . In the first half-cooler no relation was suggested, but from  $t_0 = 150^\circ$  C. to  $t_0 = 180^\circ$  C.  $t'$  may be taken as  $45$ – $50^\circ$  C.

### OBSERVATIONS

#### i.—*Preliminary measurements and other data*

| Thermometer. | Distance from entry of<br>1st half-cooler. | Thermometer. | Distance from entry of<br>2nd half-cooler. |
|--------------|--------------------------------------------|--------------|--------------------------------------------|
|              | Feet.                                      |              | Feet.                                      |
| A            | 0                                          | 7            | 0                                          |
| 1            | 18                                         | 8            | 36                                         |
| 2            | 54                                         | 9            | 72                                         |
| 3            | 90                                         | 10           | 108                                        |
| 4            | 126                                        | 11           | 144                                        |
| 5            | 162                                        | 12           | 180                                        |
| 6            | 198                                        | 13           | 216                                        |

Internal diameter of pipe, 6 inches.

External diameter of pipe,  $7\frac{1}{2}$  inches.

#### ii.—*Temperature Observations*

Complete temperature observations are exhibited below for two runs. Among the acid temperatures the column headed " $t$ " gives means of two or three half-hourly readings of temperature of every thermometer.

The water temperatures are divided horizontally into rows, each giving all the readings taken in any board, and each pair of rows those in boards at the same level; the numbers between pairs are those of the corresponding thermometers. Vertically the readings are divided into three sets of two or three columns each. The first columns of each set taken together contain all the readings taken at any one time, and, similarly, the second columns of each set are half-an-hour later than the first columns, and the third are half-an-hour later again. Thus any group of three readings, *e.g.*, 37, 34, 37, shows the successive half-hour readings at one thermometer.

RUN 18. (First half-cooler, 8th February 1918.)

*Acid Temperatures*

| Thermometer. | $y$ | $t$   | $t - t'$ |
|--------------|-----|-------|----------|
| A            | 0   | 166.5 | 120.5    |
| 1            | 18  | 155   | 109.     |
| 2            | 54  | 126.5 | 80.5     |
| 3            | 90  | 106.5 | 60.5     |
| 4            | 126 | 95.5  | 49.5     |
| 5            | 162 | 83.5  | 37.5     |
| 6            | 198 | 76.5  | 30.5     |

*Water Temperatures*

| Thermometer. | Left-hand. |    |    | Middle. |    |    | Right-hand. |    |    |
|--------------|------------|----|----|---------|----|----|-------------|----|----|
| 1            | —          | —  | —  | —       | —  | —  | —           | —  | —  |
|              | 37         | 34 | 37 | —       | —  | —  | 59          | 47 | 57 |
|              | 39         | 35 | 40 | 40      | 40 | 42 | —           | —  | —  |
| 2            | —          | —  | —  | —       | —  | —  | —           | —  | —  |
|              | 56         | 53 | 55 | 47      | 40 | —  | 54          | 55 | 55 |
|              | 47         | 47 | 49 | 47      | 54 | 54 | —           | 41 | 42 |
| 3            | —          | —  | —  | —       | —  | —  | —           | —  | —  |
|              | 49         | 49 | 49 | 46      | 47 | 45 | 48          | 48 | 47 |
|              | 43         | 41 | 44 | 51      | 49 | 51 | 48          | 49 | 48 |
| 4            | —          | —  | —  | —       | —  | —  | —           | —  | —  |
|              | 48         | 48 | 49 | 40      | 42 | 40 | 48          | 47 | 48 |
|              | 39         | —  | 44 | 42      | 43 | 42 | 41          | 42 | 48 |
| 5            | —          | —  | —  | —       | —  | —  | —           | —  | —  |
|              | 45         | 42 | 44 | 42      | —  | 40 | 48          | 49 | 47 |
|              | 40         | 40 | 40 | 45      | 42 | 45 | 41          | 46 | 49 |
| 6            | —          | —  | —  | —       | —  | —  | —           | —  | —  |

Mean 46 (neglecting first board).

RUN 21. (Second half-cooler, April 1st 1918.)

*Acid Temperatures*

| Thermometer. | $y$   | $t$  | $t - t'$ |
|--------------|-------|------|----------|
|              | Feet. |      |          |
| 7            | 0     | 57   | 39       |
| 8            | 36    | 48.5 | 30.5     |
| 9            | 72    | 43.5 | 25.5     |
| 10           | 108   | 38   | 20.0     |
| 11           | 144   | 33   | 15.0     |
| 13           | 198   | 27.5 | 9.5      |

*Water Temperatures*

| Thermometer. | Left-hand. |    | Middle. |    | Right-hand. |    |
|--------------|------------|----|---------|----|-------------|----|
| 12-13        | —          | —  | —       | —  | —           | —  |
|              | 13         | 13 | —       | —  | 10          | 10 |
| 11           | —          | —  | —       | —  | —           | —  |
|              | —          | —  | 15      | 15 | 14          | 14 |
|              | —          | —  | 17      | 16 | 14          | 14 |
| 10           | —          | —  | —       | —  | —           | —  |
|              | —          | —  | 20      | 20 | 16          | 16 |
|              | 15         | 14 | —       | —  | 18          | 18 |
| 9            | —          | —  | —       | —  | —           | —  |
|              | —          | —  | 23      | 32 | 19          | 20 |
|              | 22         | 20 | —       | —  | 21          | 21 |
| 8            | —          | —  | —       | —  | —           | —  |
|              | —          | —  | 28      | 29 | 21          | 22 |
|              | 26         | 19 | —       | —  | 25          | 25 |
| 7            | —          | —  | —       | —  | —           | —  |

Mean  $t' = 18^{\circ} \text{C.}$ *Values of Acid and Water Flow*

| Parallel Currents. |                                    |                                               |                                                    | Counter Currents. |                                    |                                               |                                                    |                                   |
|--------------------|------------------------------------|-----------------------------------------------|----------------------------------------------------|-------------------|------------------------------------|-----------------------------------------------|----------------------------------------------------|-----------------------------------|
| Run.               | Acid Flow.<br>Tons<br>per<br>hour. | $\frac{\text{C.H.U.}}{q \text{ deg. C. hr.}}$ | C                                                  | Run.              | Acid Flow.<br>Tons<br>per<br>hour. | $\frac{\text{C.H.U.}}{q \text{ deg. C. hr.}}$ | C                                                  | Water Flow.<br>gals. per<br>hour. |
| 11                 | 5.10                               | 4080                                          |                                                    | 21                | 4.72                               | 3760                                          |                                                    | 227                               |
| 12                 | 5.12                               | 4130                                          |                                                    | 22                | 4.92                               | 3930                                          |                                                    | 160                               |
| 13                 | 6.00                               | 5120                                          |                                                    | 23                | 5.16                               | 4100                                          |                                                    | 210                               |
| 14                 | 6.64                               | 5130                                          |                                                    | 24                | 5.18                               | 4160                                          |                                                    | 144                               |
| 15                 | 6.71                               | 5180                                          |                                                    | 25                | 5.18                               | 4160                                          |                                                    | 81                                |
| 16                 | 6.72                               | 5180                                          | $\frac{22 \text{ C.H.U.}}{\text{ft. hr. deg. C.}}$ | 26                | 5.47                               | 4355                                          | $\frac{14 \text{ C.H.U.}}{\text{ft. hr. deg. C.}}$ | 122                               |
| 17                 | 7.08                               | 5490                                          |                                                    | 27                | 5.77                               | 4560                                          |                                                    | 140                               |
| 18                 | 7.22                               | 5580                                          |                                                    | 28                | 6.03                               | 4810                                          |                                                    | 822                               |
| 19                 | 7.51                               | 5810                                          |                                                    | 29                | 6.18                               | 4870                                          |                                                    | 437                               |
| 20                 | 8.10                               | 6270                                          |                                                    | 30                | 7.47                               | 5780                                          |                                                    | 106                               |

## Parallel currents—First half-cooler (A)

*Acid and Water Temperatures*

| Run.             | Acid. |       |       |       |      |      |      | Water. |
|------------------|-------|-------|-------|-------|------|------|------|--------|
|                  | A     | 1     | 2     | 3     | 4    | 5    | 6    |        |
| 11               | 163   | —     | 118   | 98    | 86   | 76   | 66   | 51     |
| 12               | 162   | —     | 118   | 96    | 85.5 | 73.5 | 65   | 51     |
| 13               | 175   | 153.5 | 132   | 109.5 | 98   | 86   | 79.5 | 53     |
| 14               | 164.5 | 151   | 114   | 92    | 81   | 71   | 65.0 | 43     |
| 15               | 168.5 | 155.5 | 124   | 99.5  | 93   | 81.5 | 74.5 | 48     |
| 16               | 168   | 153.5 | 119   | 96    | 85   | 74.5 | 69   | 46     |
| 17               | 158.5 | —     | 121   | 103.5 | 92   | 81   | 73   | 51     |
| 18               | 166.5 | 155   | 126.5 | 106.5 | 98.5 | 83.5 | 76.5 | 46     |
| 19               | 168   | 145.5 | 117.5 | 90.5  | 85   | 73.5 | 68   | 43     |
| 20               | 165   | 150   | 122   | 99.5  | 94   | 84   | 79   | 52     |
| Mean Temperature | 165.9 | 152   | 122   | 99.6  | 89.4 | 78.4 | 71.6 | 48.4   |

## Counter-currents—Second half-cooler (B)

*Acid and Water Temperatures*

| Run.              | Acid. |      |      |      |      |      | Water |
|-------------------|-------|------|------|------|------|------|-------|
|                   | 7     | 8    | 9    | 10   | 11   | 13   |       |
| 21                | 57    | 48.5 | 43.5 | 38   | 33   | 27.5 | 18    |
| 22                | 52.5  | 44.5 | 39.5 | 35.5 | 30.5 | 25.5 | 16    |
| 23                | 53    | 46   | 41   | 35   | 32.5 | 28   | 17    |
| 24                | 64.5  | 55   | 48.5 | 42   | 36.5 | 31.5 | 19    |
| 25                | 62.5  | 54   | 48.5 | 43.5 | 46   | 35   | 21    |
| 26                | 60.0  | 51.5 | 46   | 41.5 | 37   | 31   | 19    |
| 27                | 53.5  | 55.5 | 50   | 45   | 41   | 35   | 22    |
| 28                | 37.5  | 48.5 | 42.5 | 36.5 | 32.5 | 26.5 | 15    |
| 29                | 58.5  | 51   | 46.5 | 40.5 | 36   | 30.5 | 17    |
| 30                | 63.5  | 57.5 | 53   | 48   | 44   | 39   | 23    |
| Mean Temperature. | 59.2  | 51.2 | 45.9 | 46.5 | 36.3 | 30.9 | 18.7  |

The calculation of the mean over-all coefficient of transmission (C) has been made from these observations in the following way. Considering the case of parallel-current working, the mean temperature for Therm. A

has been calculated for the ten runs from No. 11–No. 20; similarly for of the others. These means are recorded on the bottom line of the Table A.

These means for the acid being added and divided by the number of them gives a true mean temperature of the acid at all points. Subtracting from this the mean temperature of the water gives the mean difference of temperature between the two liquids.\*

This is found to be  $111.4 - 48.4 = 62.8^{\circ} \text{C}$ .

In the same way the values of  $q$  (Table B) are averaged. This mean multiplied by the mean extreme fall of temperature ( $165.9 - 71.6$ ) gives the total heat transferred per hour; and when this is divided by the total surface and by the mean value of  $t - t'$  (*i.e.*,  $62.8$ ) the over-all coefficient is obtained. Its value is  $22 \text{ C.H.U./ft.}^2/\text{hour/deg. C}$ .

The counter-current set is then treated in the same way. For this case the value of  $C$  is  $14 \text{ C.H.U./ft.}^2/\text{hour/deg. C}$ .

It is not justifiable to argue from these numbers, either for or against counter-current practice. The difference of average temperature in the two cases is quite sufficient to account for the difference in the value of  $C$ . In the parallel current the mean temperature of the acid was  $111.2^{\circ} \text{C}$ ., while in the counter-current case it was only  $44^{\circ} \text{C}$ .

A reference to the alignment chart for liquids (Fig. 3) will show how influential the temperature is.

These very extensive and complete sets of observations (more complete than anything that had previously been done) are sufficient to form the basis of design as long as the conditions are not much departed from. But it must be remembered that any increase in the average temperature or in the velocity of flow will increase the coefficient and decrease of either will diminish it.

The design of an installation to cool a specified quantity of acid through a specified range of temperature is best effected by means of Fig. 5. For example, if 6 tons of acid are to be cooled from  $105^{\circ} \text{C}$ . to  $30^{\circ} \text{C}$ . per hour.

The value of  $q$  is  $6 \times 2240 \times .35$ , where  $.35$  is taken as the specific heat of the acid, thus  $q = 4700$ .

Taking the coefficient of transmission as being 20, the value of  $h$  on support  $C$  is found to be about 33. Joining this point with 4700 on support  $D$ , the value 130 is found on support  $E$ . This requires multiplying by  $n = \frac{q}{q'}$ . Now if about 2,300 lb. of water flow per hour

over the outside  $\frac{q}{q'} = 2$  nearly. If the exit temperature of the water is  $19^{\circ}$ , the economic factor is 0.9, *i.e.*, .9 of the maximum amount of heat is transmitted; hence the value of  $N$  is 1.71, as given by the table in the chart. The length of pipe necessary is therefore

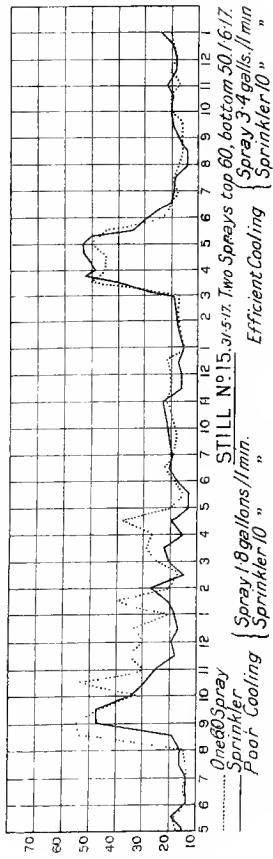
$$130 \times 1.71 = 181 \text{ feet.}$$

---

\* This method is much better than taking any of the usual formulæ, which assume that the fall of temperature along the pipe follows some assigned law.



GRAPH I.



GRAPH II A.

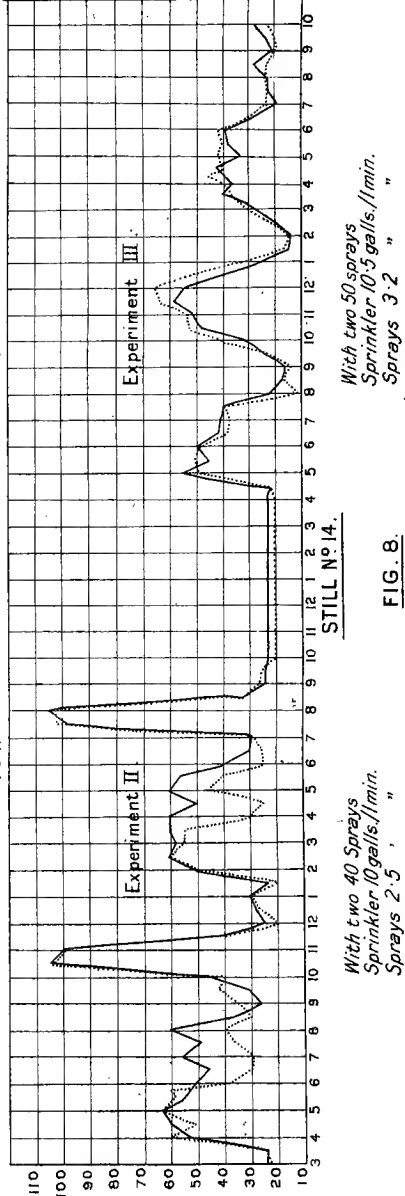
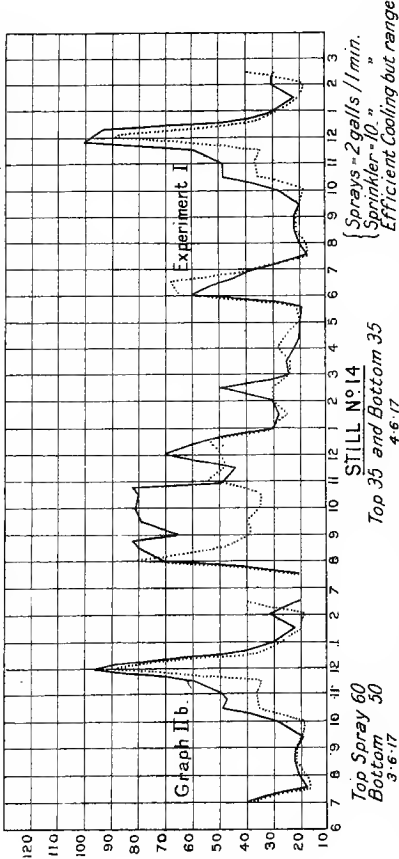


FIG. 8.

If one is content with an 80 per cent. transmission, the length of the pipe need only be 143 feet.

**Acid Coolers at Queen's Ferry (Grillo Plant).**—The following tests were made at Queen's Ferry on the acid coolers in the Grillo plant there. This cooler had nine straight pipes, each 8 feet long. All the straight lengths and four of the bends were under water. Internal diameter of pipes 5 inches, and external diameter 6 inches.

External cooling area = 126 square feet.

The specific heat of 20 per cent. oleum is 0.33; the quantity dealt with, 22,400 lb. per hour. Holes were drilled in the pipes leading to and from the cooler, and pockets put in so that the temperatures could be determined. The temperature on entering from the towers was 65–68° C.; that on leaving the cooler 48–49° C.; so that the average cooling is about 18° C.

The total heat transferred is, therefore,

$$22400 \times 0.33 \times 18 = 134388 \text{ C.H.U./hour,}$$

and the amount per square foot of surface

$$\frac{22400 \times 0.33 \times 18}{126} = 1056 \text{ C.H.U./ft.}^2\text{/hour.}$$

The temperature of the water was not given in the report.

**Water Economy and Efficient Cooling Nitro-Cotton Spent Acid Stills.**—The rate of delivery of both sprays and sprinklers was carefully measured under similar conditions. The graphs (Fig. 8) show cooling curves plotted from readings made simultaneously with a sprinkler, using what common practice required, *i.e.*, 10 gallons per minute. The keys to the graph show the sprays used in each experiment.

*Graph I* gives the results of one inverted 60-spray, and the cooling was not efficient.

Water consumed = 2 gall. per min. on spray.

Water consumed = 10 gall. per min. on sprinkler.

*Graph II* was much more satisfactory, for here, taking 10 gall. per min. as standard, the two cooling curves approximate—

Water consumed = 3.5 gall. per min. on sprays.

Water consumed = 10 gall. per min. on sprinkler.

Experiments were then repeated with double sprays, starting with 35, 40, 50, and then 60-sprays, and the results were plotted.

Two 35-sprays consume 2 gallons per min.

Two 40-sprays consume 2.5 gallons per min.

Two 50-sprays consume 3.2 gallons per min.

Two 60-sprays consume 3.6 gallons per min.

So that, using two 60-sprays, which appear to give satisfactory results, one saves per coil at least 6 gall. per min., which is equivalent to 362,880 gallons per day.

**Lead Coolers in Denitration Plant.**—In a report entitled: Notes on the DNA (denitrated acid) coolers (T.N.T. denitrators), particulars are given of the performance of D.N.A. coolers which had newly been installed at Queen's Ferry. The only advantage these coolers have over the old type, and the only way in which they differ, is in the water jacket, which now extends to the base of the cooler and is not only a shallow cup, as was previously the case.

*Measurements.*—Each cooler is 2 ft. 6 in. in diameter and is 3 ft. 6 in. high. It is surrounded by a water jacket 2 ft. 10 in. in diameter, so that there is a jacket of water 2 in. thick encircling the cooler. The lead sheeting of the coolers is about  $\frac{5}{16}$  in. material, weighing 12 lb./sq. ft.

*Coils.*—Inside each cooler are two coils—22 in. and 15 in. diameter respectively—the latter coil fitting comfortably inside the former. The larger coil has 10 turns of 22 in. each; the smaller has 10 turns of 15 in. each. Both coils are of 2 in. lead pipe. There are three coolers for every two columns. Each column feeds directly into its own cooler—these two coolers feeding into a third common cooler—and from here to the acid main and storage.

*Cooling surface.*—The total cooling surface offered by unit cooler is the surface offered by the lead coils, added to that offered by the superficial surface of lead in the water jacket.

(1) 39·3 feet length of 2-in. lead = 20·6 square feet surface in small coil.

(2) 57·6 feet length of 2-in. lead = 30·2 square feet surface in large coil.

(3)  $\frac{5}{2} \cdot \frac{22}{7} \cdot \frac{7}{2} = 27·5$  square feet in water jacket.

Total surface offered per coil = 78·3 sq. ft.

The D.N.A. issues from the columns at a temperature, approximately, 150° C.

The maximum production of D.N.A. per column was about 58 tons daily.

Over an experimental run of *two* columns the following data were obtained:

Rate of production of D.N.A. = 58 tons/day/column.

Temperature of D.N.A. in boot, 150° C.

Temperature of D.N.A. leaving 1st cooler, 68° C.

Loss of temperature in 1st cooler, 150–68 = 82° C.

Temperature of D.N.A. leaving middle cooler = 40° C.

Loss of temperature in middle cooler = 28° C.

Temperature of water from 1st cooler = 45° C.

Amount of water used in cooler per day = 90 tons.

Temperature of water from middle cooler = 30° C.

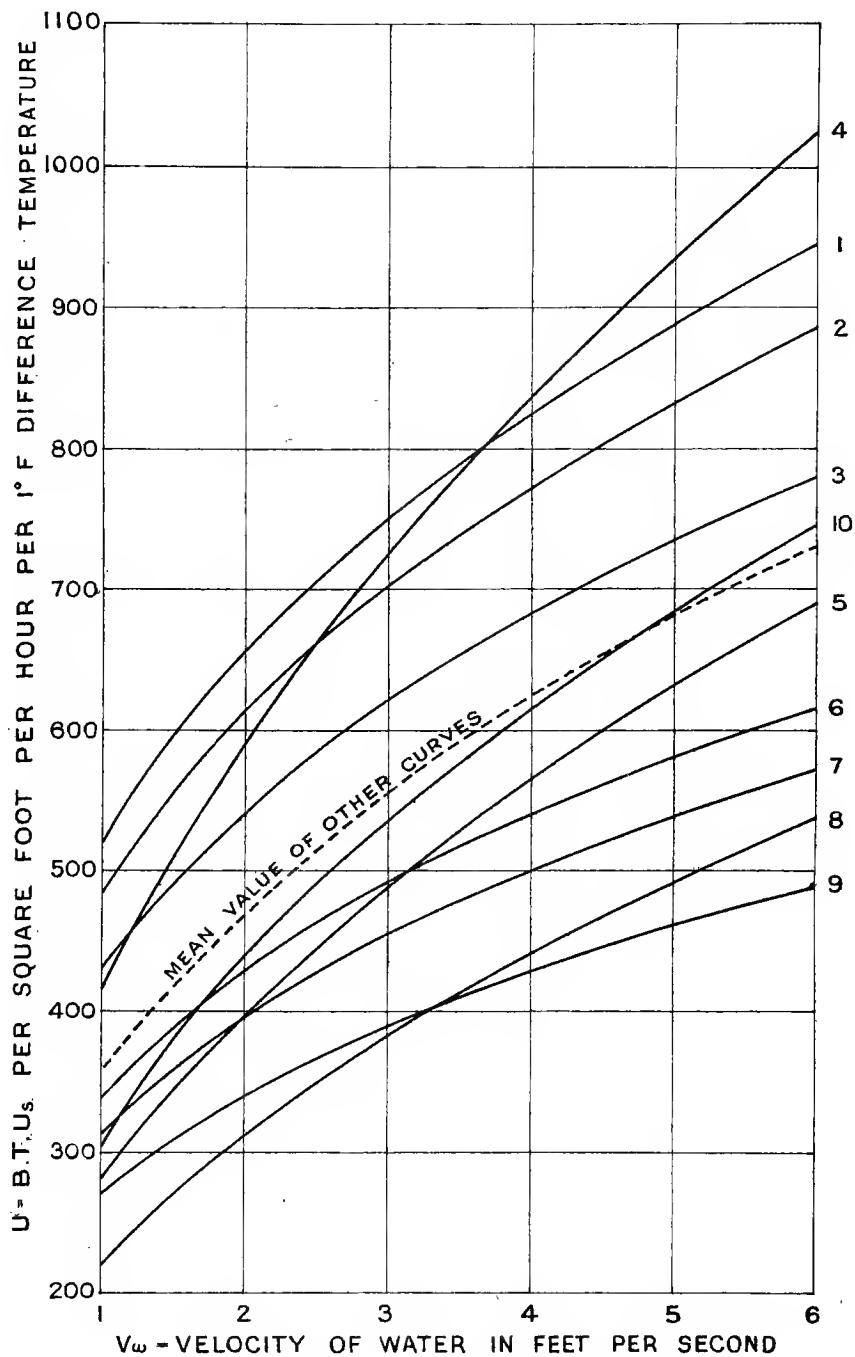
Amount of water used in middle cooler per day = 80 tons.



# COEFFICIENTS OF HEAT TRANSMISSION IN SURFACE CONDENSERS

(STEAM TO WATER)

## RELATION OF $U_s V_w$ (AVERAGE EXPERIMENTAL VALUES)



- |             |                      |
|-------------|----------------------|
| 1. Ser      | 6. Stanton           |
| 2. Josse    | 7. Joule             |
| 3. Weighton | 8. Allen             |
| 4. Hepburn  | 9. Clement & Garland |
| 5. Hageman  | 10. Orrok            |

FIG. 9

The heat given out by cooling acid

$$= (58 \times 2240) \times 0.48 \times (150 - 40). \\ = 6,859,776 \text{ C.H.U.}$$

Heat accounted for in 1st cooler

90 tons water raised from 18° to 45° C.

$$\text{Heat} \times 90 \times 2240 \times 27 \\ = 5443200 \text{ C.H.U.}$$

In middle cooler

80 tons of water raised from 18° to 30° C. —

half of this rise is due to acid from the second column.

Heat due to acid from 1st column

$$= 80 \times 2240 \times 6 \\ = 1,075,200 \text{ C.H.U.}$$

So that the total amount of heat accounted for is

$$5,443,200 + 1,075,200 \\ = 6,518,400 \text{ C.H.U.}$$

The difference between this and that lost by acid is 341,376 C.H.U.  
This is to be accounted for by radiation, &c.

Total surface of coolers and liquid, 100 sq. ft.

$$\text{So radiation loss} = \frac{341,376}{100 \times 24} \\ = 142 \text{ C.H.U./hr./ft.}^2$$

[Taking the temperature excess above surroundings as 45°, the emissivity =  $\frac{142}{45} = 3.1$ , which is about the standard value.]

From the data given above it is found that 83 per cent. of the total cooling is done in the first cooler.

$$\text{In this cooler } \frac{5,443,200}{24 \times 78.3} = 2896 \text{ C.H.U./hr./ft.}^2 \text{ are accounted for;}$$

this is equivalent to a coefficient of transmission of

$$\frac{2896}{76} = 38.1 \text{ C.H.U./hr./ft.}^2/\text{deg. C.}$$

[This assumes initial temperature of water to be about 15° C.]

In the middle cooler the heat transmitted is

$$\frac{1,075,200 \times 2}{24 \times 78.5} = 1144 \text{ C.H.U./hr./ft.}^2$$

This is equivalent to a coefficient of transmission of

$$\frac{1144}{31} = 37 \text{ C.H.U./hr./ft.}^2/\text{deg. C.}$$

These coolers are very efficient and, if installed throughout, the D.N.A. could be passed at 40° C. to the storage tank.

Data are also given for a large open cooler between the column and the tank house. In this shallow water trough there are seven tubes of 49 ft. length each; the tubes are of  $2\frac{1}{2}$  in. lead pipe. Therefore the total surface offered to the cooling water is

$$\frac{5}{2} \times \frac{22}{7} \times \frac{49}{12} \times 7 = 224.6 \text{ sq. ft.}$$

Over an experimental run the following data were obtained.

|                                          |   |   |           |
|------------------------------------------|---|---|-----------|
| Number of columns working -              | - | - | 8         |
| D.N.A. produced -                        | - | - | 440 tons. |
| Water entering at                        | - | - | 18° C.    |
| And passing cooler at                    | - | - | 26° C.    |
| Amount of water used per day             |   |   | 200 tons. |
| Temperature of D.N.A. entering 5 columns |   |   | 83° C.    |
| Temperature of D.N.A. leaving 5 columns  |   |   | 74° C.    |
| Temperature of D.N.A. entering 3 columns |   |   | 68° C.    |
| Temperature of D.N.A. leaving 3 columns  | - |   | 60° C.    |

Therefore total heat transferred from acid per day is

$$\begin{aligned} & 275 \times 2240 \times 0.46 \times 9 \\ & + 165 \times 2240 \times 0.46 \times 8 \\ & = 3,910,368 \text{ C.H.U./day.} \end{aligned}$$

In one day 200 tons of water are raised from 18° — 26° C. This represents  $(200 \times 2240 \times 8)$ .

$$= 3,584,000 \text{ C.H.U./day.}$$

which leaves a difference of 326,368 C.H.U. to be accounted for by radiation, &c. The loss per sq. ft. of surface per hour is

$$\frac{325,368}{24 \times 224.6} = 60 \text{ C.H.U./hr./sq. ft.}$$

Since the excess temperature is probably only about 4° C. on the average, this implies a loss about five times as great as by ordinary emission, the excess being due to evaporation.

The cooling is done at the rate of

$$\frac{3,910,368}{224.6 \times 24} = 740 \text{ C.H.U./hr./ft.}^2$$

The average fall across pipe wall is 51° C.; hence the coefficient of transmission is about 14.5.

**Superheater at Denitration Plant.**—The following particulars are given of the performance of a superheater at a denitration plant. The superheater consisted of 30 tubes, and 18 ft.  $\times$   $1\frac{3}{4}$  in. internal and 2 in. external diameter. The total heating surface was

$$30 \times 18 \times \frac{2}{12} \times \frac{22}{7} = 283 \text{ sq. ft.}$$

The steam required at 60 lb. gauge is 130 lb./min.

Required temperature of superheated steam - = 200° C.

Temperature of 60 lb. steam - = 140° C.

∴ Superheat - - - - = 60° C.

Heat required per minute  $130 \times 0.47 \times 60 = 3666 \frac{\text{C.H.U.}}{\text{min.}}$

*i.e.*, each square foot of heating surface must transmit

$$\frac{3666}{283} = 13 \text{ C.H.U./min.} = 780 \text{ C.H.U./hr.}$$

The gas required is calculated from the following data :—

1 cubic foot producer gas gives out 120 B.Th.U. = 67 C.H.U.

Hence the number of cubic feet required is  $\frac{3666}{67} = 55 \frac{\text{cub. ft.}}{\text{min.}}$

= 79,200 cub. ft./day.

Assuming 10 per cent. loss by radiation from boiler work and 20 per cent. loss on waste gases, the number of cubic feet required must be increased to 120,000.

Since 1 ton coal yields, approximately, 140,000 cub. ft. of gas, it follows that about 1 ton of coal per. day will be required to correspond to the heat required for the denitration of 500 tons of spent acid,

*i.e.*, for 84 tons T.N.T.

To determine the temperature of the mixed gases 5,000 cub. ft. of gas + 15,000 cub. ft. air = approx., 20,000 cub. ft. of burnt gases

The weight of this is (approx.)  $\frac{20,000}{12.4} \text{ lb.}$

Specific heat 0.25

Thermal value of 5,000 cub. ft. gas =  $5000 \times 67 \text{ C.H.U.}$  Therefore the rise of temperature produced by combustion is

$$\frac{5000 \times 67 \times 12.4}{20000 \times 0.25} = 800^\circ \text{ C.}$$

Since the gas will not cool below 200° C., and the rise is calculated from the quantity of heat which is to be transmitted, the initial temperature must be 100° at least, and the actual coal required will be more nearly  $1\frac{1}{4}$  tons per day.

Assuming this, the temperature difference on the two sides of the tubes will be

At inlet, at least 104–140 - - = 900° C.

At exit, at least - - = 40° C.

The mean difference is  $\frac{900-40}{\log_e \frac{900}{40}} = 276^\circ \text{ C.}$

and the corresponding coefficient of transmission would be

$$\frac{780}{276} = 2.8 \text{ C.H.U./hr./ft.}^2\text{/deg. C.}$$

But the exit temperature of the flue gases might easily be higher in practice, and a larger coefficient would be necessary. This is, however, a very small requirement.

**The effect of stirring.**—In a Report on Experiments on the continuous cooling of a liquid, the question of the effect of stirring is examined; the object being to determine whether the efficiency of a continuous cooler, of the type which consists of a water coil in an upright cylindrical vessel, is increased by stirring the liquid surrounding the coil.

*Summary.*—Experiments conducted parallel to one another show that in the apparatus used the efficiency with stirring is only about 85 per cent. of that without stirring.

*Experimental.*—An experimental T.N.T. nitrator was converted into a cooler by fitting it with an overflow "swan-neck," arranged so that a liquid fed into the top of the vessel would flow out at the bottom, the volume of liquid (90 gallons) in the vessel remaining constant.

The cooling coils consisted of two 45-foot lengths of lead pipe (external diameter  $1\frac{1}{4}$  in.) wound into heart-shaped spirals of the same size, and arranged so that the turns of one length alternated with those of the other. The total cooling surface (outside surface of the two lengths of pipe) was 29.3 sq. ft.

The stirrer was of the disk type, similar to those in use in the pots of the continuous washing plant; it was fitted eccentrically in the cylindrical vessel and rotated at about 160 revolutions per minute.

Hot water at  $85^{\circ}$  C. was fed continuously into the cooler by a pipe just dipping below the surface of the liquid. The feed was kept constant in quantity by maintaining a constant heat in the feed vessel, and constant in temperature at  $84$ – $85^{\circ}$  C. by means of an adjusted supply of live steam to the feed vessel. The temperatures (1) of the inlet water, and (2) of the outlet water, were read every five minutes by means of thermometers: (1) fixed in a T-piece in the inlet pipe; and (2) inserted in the swan-neck respectively. The exit water overflowed through the swan-neck and the rate of flow was measured by determining the time taken to fill a calibrated barrel.

Cold water ( $18$ – $21^{\circ}$  C.) was passed through the coils to affect cooling. The water inlets were at the bottom and the outlets at the top. The rate of flow was determined by measuring the time taken to fill two calibrated vessels used alternately; it was kept practically constant at 10 gallons per minute.

*Experiment 1.*—The whole arrangement was first allowed to settle down to a steady condition, with the stirrer out of action; the rates of flow, temperatures, &c., were then measured over two consecutive periods of 20 minutes each. The stirrer was then started, and when a steady state was obtained the measurements were again made over two consecutive 20-minute periods. The results obtained are shown in Table I.

It was intended that the rate of flow of hot water should be the same throughout, but it was found that while the stirrer was in action the rate of flow was less than during the earlier part of the experiment without stirring.

TABLE I.

|                                       | Stirrer.                                                                               |                                                              |
|---------------------------------------|----------------------------------------------------------------------------------------|--------------------------------------------------------------|
|                                       | Stationary.                                                                            | Rotating.                                                    |
| Inlet water temperature               | <div style="text-align: right;">°</div> Lowest - 83.5<br>Highest - 85.5<br>Mean - 84.6 | <div style="text-align: right;">°</div> 83.2<br>86.1<br>84.9 |
| Exit water temperature -              | Lowest - 28.0<br>Highest 29.0<br>Mean 28.3                                             | 85.0<br>35.5<br>35.2                                         |
| Flow of hot water, gallons per minute | 1st period 1.93<br>2nd period 2.02<br>Average 1.97                                     | 1.73<br>1.73<br>1.73                                         |

Temperature of cooling water, 18° C.

Rate of flow of cooling water, 10 gall./min.

Rate of stirring, 160 revolutions per minute.

Thus with the stirrer rotating, although the cooling was favoured by the circumstances that the flow of hot water was 13 per cent. less, the fall of temperature produced by the cooler was 11 per cent. less than when the stirrer was stationary.

In this experiment the flow of hot water was different in the two regimes.

*Experiment 2.*—In order that the results might be strictly comparable, the experiment was repeated and the rate of flow of the hot water maintained the same, whether the stirrer was stationary or rotating. The rate of flow was somewhat lower than in Experiment 1. After the run with the stirrer rotating was finished, the stirrer was stopped and another series of observations made in order to determine how accurately the apparatus would regain its original state of equilibrium. The results are shown in Table II.

TABLE II.

|                                   | Stirrer.              |                      |           |      |
|-----------------------------------|-----------------------|----------------------|-----------|------|
|                                   | Stationary.           |                      | Rotating. |      |
|                                   | (1)                   | (2)                  |           |      |
|                                   | Before rotation.<br>° | After rotation.<br>° | °         |      |
| Inlet water temperature -         | Lowest                | 85.0                 | 85.2      | 84.0 |
|                                   | Highest               | 87.5                 | 85.6      | 87.0 |
|                                   | Average of all        | 85.8                 | 86.1      | 84.6 |
| Exit water temperature            | Lowest                | 24.2                 | 24.0      | 32.2 |
|                                   | Highest -             | 27.4                 | 24.7      | 33.2 |
|                                   | Average -             | 25.4                 | 24.3      | 32.7 |
| Flow of hot water, gall. per min. | 1st period -          | 1.58                 | 1.65      | 1.58 |
|                                   | 2nd period            | 1.58                 | 1.52      | 1.58 |
|                                   | Average               | 1.58                 | 1.58      | 1.58 |

Temperature of cooling water, 21° C.

Rate of flow of cooling water, 10 gallons/minute.

Rate of stirring, 156 revolutions per minute.

Summary Table

|                                                                | Stirrer.    |           |
|----------------------------------------------------------------|-------------|-----------|
|                                                                | Stationary. | Rotating. |
| Heat removed per min., in degree/gallons Table I.<br>Table II. | 110<br>96   | 86<br>82  |

Thus notwithstanding the more favourable final difference in temperature between cooling water and cooled effluent, cooling is only about 80 per cent. as efficient with stirring as without.

[*Note by Compiler.*—The most obvious explanation of these unexpected results is that the action of the stirrer set up such a current that a fair proportion of the hot water was swept down to the outlet without coming into contact with the pipes. This must always be possible if the pipes do not occupy a great portion of the tank. If so, the experiments illustrate the bad action of a defect in design which is to be guarded against.]

**Surface condensers.**—Fig. 9 is drawn up to show at a glance the order of value of the coefficient of transmission in the case of surface condensers. The abscissæ give the velocity of the condenser-water in

TOTAL HEAT LOSS FROM IRON SURFACES  
in C.H.U. per sq. ft. per hr.  
FOR DIFFERENT EXCESS TEMPERATURES.

From N.P.L. expts. on large surfaces in ordinary condition.

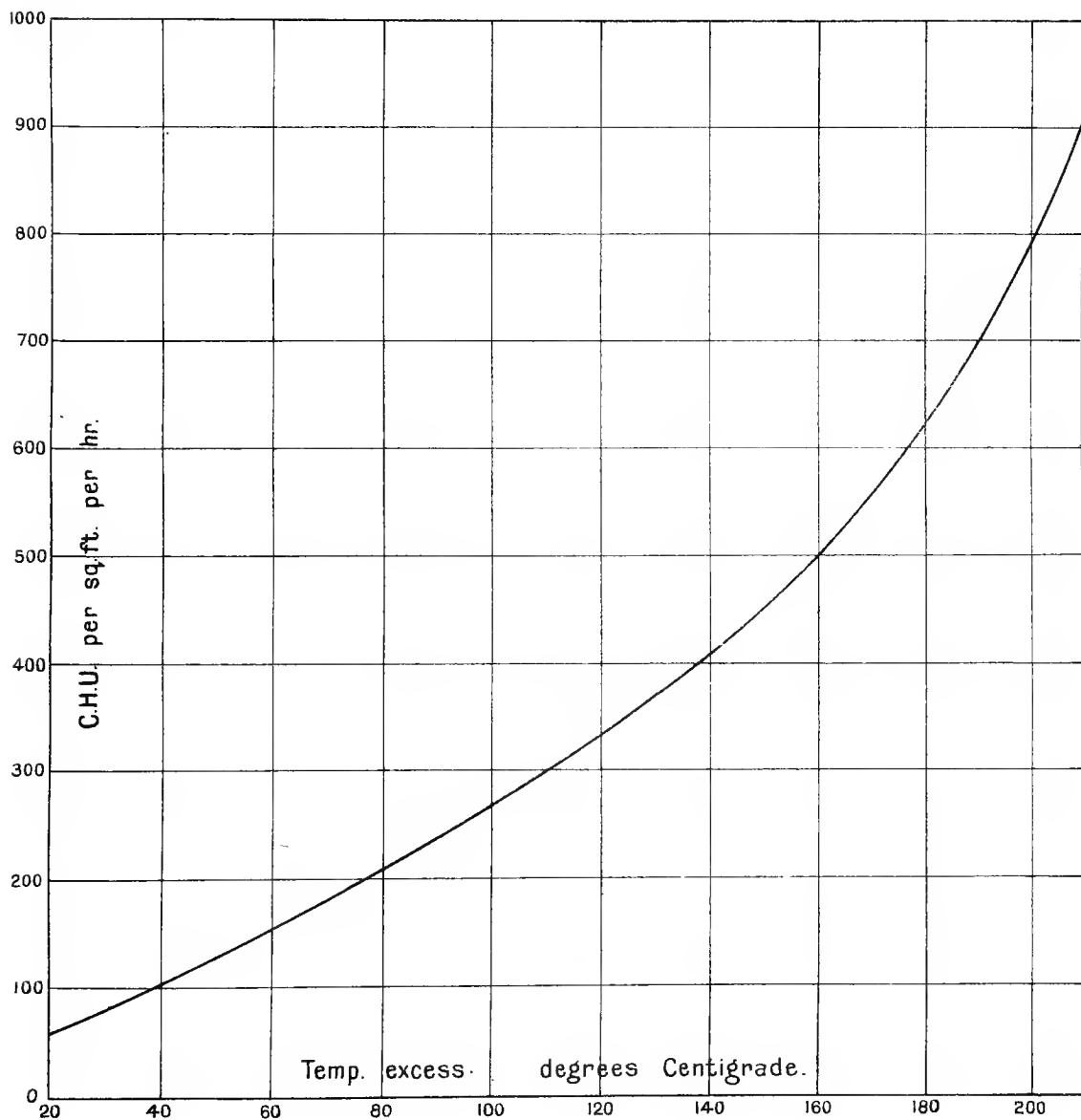
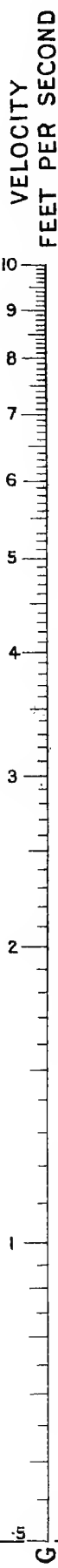


FIG. II.



DIAMETER OF PIPE IN INCHES.



# FLOW OF WATER THROUGH CAST IRON PIPES.

- A. BOX
- B. NAT-PH-LAB.
- C. GOODMAN.
- D. EYTELWEIN.

HEAD PRODUCING FLOW, PER 100 FEET RUN.

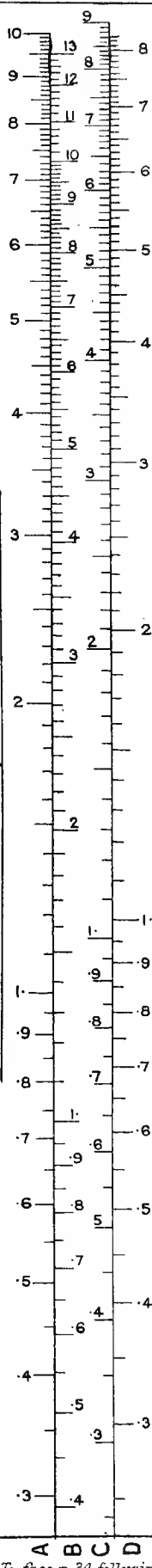


FIG. 12.



feet per second. This is a very important contributing factor, but it is not the only one. A large number of other factors enter: temperature of water, diameter of tubes, velocity of steam, &c. The large difference, shown in the chart, between the results for different observers, must be attributed to these causes.

**Heat interchange in a cylinder in which a heat-producing reaction takes place.** (Fig. 10.)

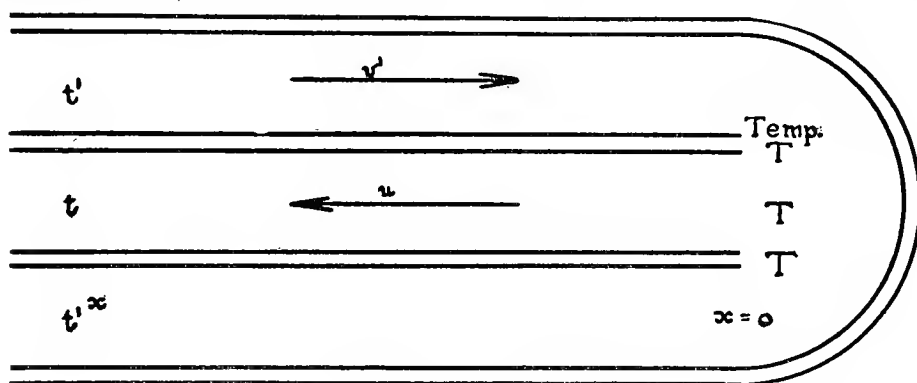


FIG. 10.

The kind of case referred to is that in which gas is continuously delivered into a reaction bomb, and passes along an inner cylinder which contains a catalytic agent, which causes chemical action to occur. In this reaction a certain amount of heat,  $h$ , is set free *per unit length* of the reaction cylinder.

Similar considerations to those entertained before show that the temperatures, in the steady state, are given by the formulæ

$$t' = T - \frac{2\pi a.Ch}{2q^2}x^2 \quad t = T + \frac{2\pi a.Ch}{2q^2}x^2 + h\left(\frac{x}{q}\right)$$

where  $q$  is the thermal capacity of the flowing gas per unit time (assumed to be the same before and after reaction), and  $C$  is the coefficient of transmission.

It follows that the difference between the outlet and inlet temperatures is  $hl/q$ , where  $l$  is the length of the cylinder.

This last result is somewhat unexpected, because it shows that the difference between outlet and inlet temperatures is independent of the conductivity and dimensions of the wall of the cylinder *when the steady state is reached*. The explanation is that any heat that is conducted through the cylinder is brought back again by convection. The problem is different from that of ordinary interchange, because in the present case the identical material flows through both outer and inner cylinders in succession.

**Surface loss.** —No allowance is made in the above theoretical reports for the loss of heat from the outside surface of an interchanger. This allowance is best made separately, especially as in most cases it can only be made in a very approximate way, because of the great influence played by draughts over the surface. The loss is partly due to

radiation, the relative importance of which is greater at high temperatures; and partly due to conduction and convection through the air. The accompanying chart represents experiments conducted at the National Physical Laboratory, Teddington. It gives the heat loss arising from all causes per square foot of large surfaces under ordinary conditions, at various excess temperatures above the surroundings.

*Alignment Chart for flow of Water in Pipes.*

In Fig. 12 an alignment chart is given for calculating the flow of water in cylindrical pipes in gallons per minute and also the head required (in fractions of a foot per hundred foot run) when the data are the diameter of the pipes in inches, and the linear velocity in feet per second.

The appropriate diameter (scale E) and velocity (scale G) being joined, the intersection of the join with scale F gives the gallons per minute and with scales A, B, C, D the head according to four different authorities. Example: When the diameter is 10 inches and the velocity is 6 feet per second, the number of gallons per minute is 1,180, and the head, according to Goodman, 1.6 feet per 100 feet.

According to Unwin this value should be 1.36 feet per 100 feet.

**Application of the principle of Quinan's bubbler-scrubber to the cooling of condenser water.**—In this system the gas or air is forced upwards through a layer of liquid supported on a perforated diaphragm, the velocity of the air or gas being sufficiently great to prevent the liquid from passing downwards through the small perforations. Intimate contact is thus effected between the liquid and the gas. The liquid is circulated by means of a pump.

In the cases under consideration the holes are  $\frac{1}{8}$  in. in diameter, spaced  $\frac{3}{8}$  in. centre to centre.

Analysis of cooler required to reduce the temperature of 1,000 lb. of water per hour from 98° F. to 80° F. Air temperature 60° F. and 70 per cent. saturation, on the assumption that holes in plates are  $\frac{1}{2}$  in. diameter.

*Amount of air passed through  $\frac{1}{8}$  in. diameter hole for various pressure differentials*

The velocity of efflux from short cylindrical tubes may be calculated from the following formula. (See Kent's Pocket Book, page 485.)

$$V = 353 c \sqrt{\frac{h}{p}} \text{ in which}$$

$V$  = velocity in feet per second.

$c$  = a co-efficient = 0.83 for short tubes.

$h$  = difference in pressure at each end of tube in inches of water.

$p$  = barometric pressure in inches of mercury.

Assuming  $p = 30$  ins., then formula becomes

$$v = 293 \sqrt{\frac{h}{30}}$$

*Velocities for various pressure differentials*

TABLE No. 1.

| $h =$<br>inches water. | $\frac{h}{30}$ | $\sqrt{\frac{h}{30}}$ | $298 \sqrt{\frac{h}{30}} + V$<br>Feet per second. |
|------------------------|----------------|-----------------------|---------------------------------------------------|
| $\frac{1}{4}$          | ·00833         | ·0913                 | 27·2                                              |
| $\frac{1}{2}$          | ·01666         | ·129                  | 38·4                                              |
| $\frac{3}{4}$          | ·02500         | ·158                  | 47·1                                              |
| 1                      | ·0333          | ·181                  | 54·0                                              |
| $1\frac{1}{4}$         | ·0417          | ·204                  | 61·7                                              |
| $1\frac{1}{2}$         | ·0500          | ·223                  | 66·5                                              |
| $1\frac{3}{4}$         | ·0583          | ·242                  | 72·0                                              |
| 2                      | ·0666          | ·258                  | 76·9                                              |
| $2\frac{1}{2}$         | ·0833          | ·288                  | 85·8                                              |
| 3                      | ·1000          | ·316                  | 94·3                                              |

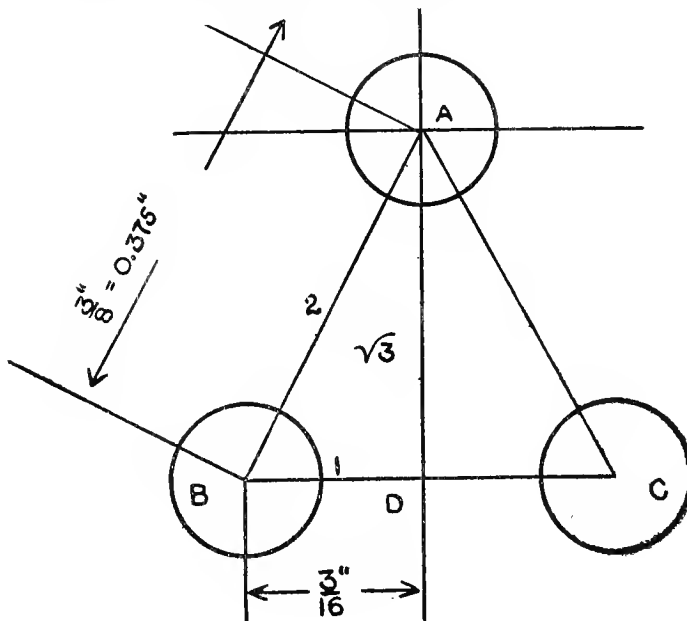
Area of  $\frac{1}{8}$  in. diameter hole = 0·01227 square inches = 0·0000882 sq. ft.

*Cubic feet of air passed through 1 hole per second.*

TABLE No. 2.

| $h$        | $\frac{1}{4}$ in. | $\frac{1}{2}$ in. | $\frac{3}{4}$ in. | 1 in.  | $1\frac{1}{4}$ in. | $1\frac{1}{2}$ in. | $1\frac{3}{4}$ in. | 2 in.  | $2\frac{1}{2}$ in. | 3 in.  |
|------------|-------------------|-------------------|-------------------|--------|--------------------|--------------------|--------------------|--------|--------------------|--------|
| Cubic feet | ·0024             | ·00338            | ·00415            | ·00476 | ·00543             | ·00586             | ·00634             | ·00678 | ·00756             | ·00831 |

*Volume of air which will pass through plate.*



Assuming holes to be spaced  $\frac{3}{8}$  in. centre to centre in each direction.

$$\text{Area of triangle } A B C = \frac{B C \times \frac{A D}{2}}{2}$$

$$A D = A B \times \sqrt{\frac{3}{2}}$$

$$\therefore \frac{A D}{2} = A B \times \sqrt{\frac{3}{4}}$$

$$= 0.375 \times 0.43$$

$$= 0.1628.$$

And area of triangle

$A B C$

$$= 0.375 \times 0.1628$$

$$= 0.061 \text{ square inches}$$

From sketch we see that triangle  $A B C$  contains one-half of a  $\frac{1}{8}$  in. hole.  $\therefore$  area of plate per hole  $= 0.061 = 0.122$  square inches and number of holes per square foot of plate

$$= \frac{144}{0.122} = 1180.$$

Volume of air passed through one square foot of plate for various pressure differentials.

TABLE No. 3.

| $h$                     | $\frac{1}{4}$ in. | $\frac{1}{2}$ in. | $\frac{3}{4}$ in. | 1 in. | $1\frac{1}{4}$ in. | $1\frac{1}{2}$ in. | $1\frac{3}{4}$ in. | 2 in. | $2\frac{1}{2}$ in. | 3 in. |
|-------------------------|-------------------|-------------------|-------------------|-------|--------------------|--------------------|--------------------|-------|--------------------|-------|
| Cubic feet air per sec. | 2.83              | 3.99              | 4.90              | 5.61  | 6.41               | 6.92               | 7.48               | 8.00  | 8.92               | 9.80  |

Weight of water passed over one foot length of plate at a velocity of 1 foot per second for various depths of liquid on plate.

TABLE No. 4.

| $h$                           | $\frac{1}{4}$ | $\frac{1}{2}$ | $\frac{3}{4}$ | 1    | $1\frac{1}{4}$ | $1\frac{1}{2}$ | $1\frac{3}{4}$ | 2     | $2\frac{1}{2}$ | 3     |
|-------------------------------|---------------|---------------|---------------|------|----------------|----------------|----------------|-------|----------------|-------|
| Pounds water passing per sec. | 1.30          | 2.61          | 3.91          | 5.21 | 6.51           | 7.82           | 9.11           | 10.42 | 13.03          | 15.63 |



CURVE NO. 1.

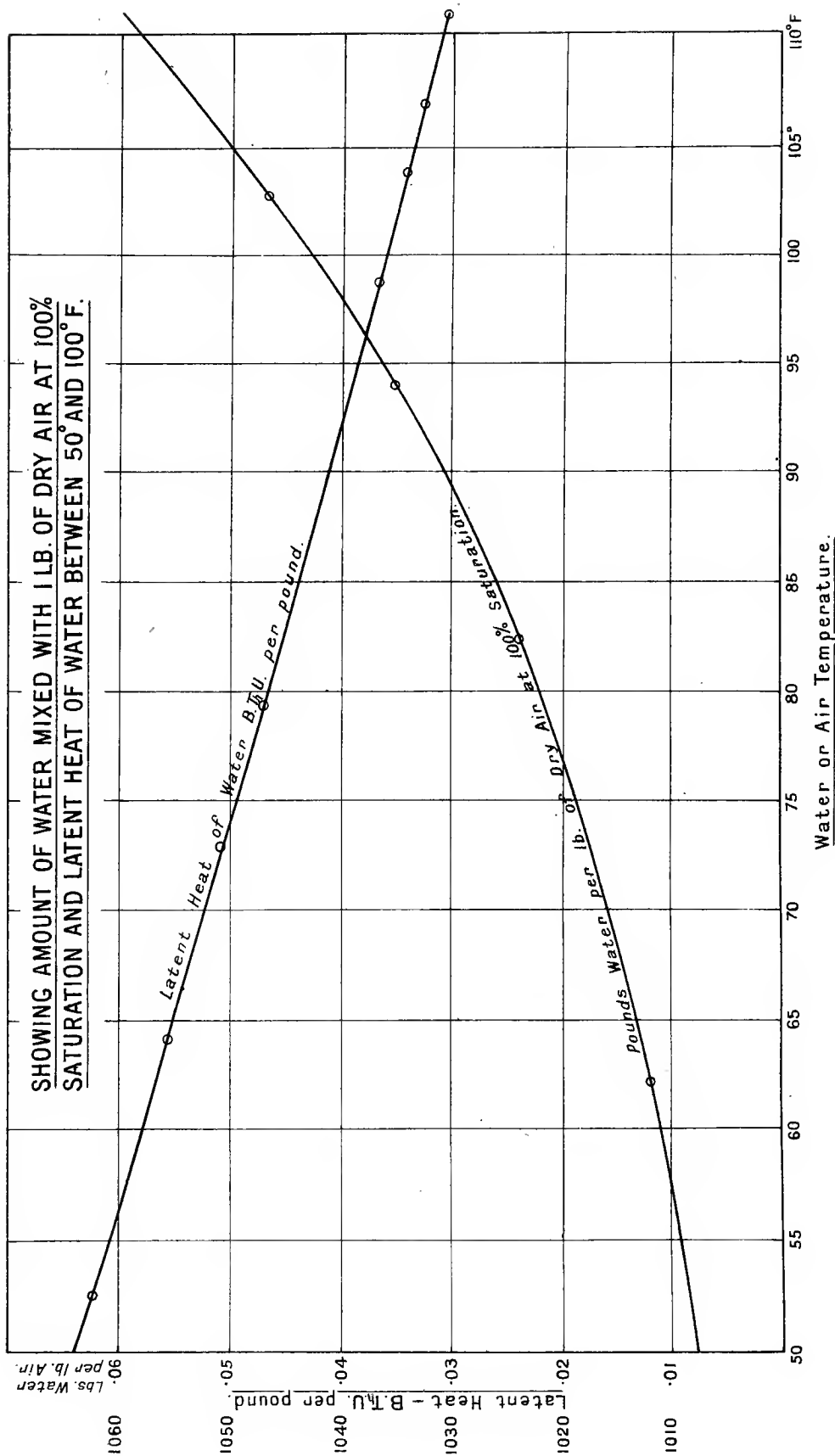


FIG. 13.

*Temperature gradient of water passing over 1 foot length of plate for various velocities. Depth of liquid =  $\frac{3}{4}$  in.*

*Velocity 1 foot per second.—*

From Table 4 we have water passing = 3.91 lb. per sec.

From Table 3 we have air passing through 1 square foot of plate = 4.9 cubic feet per second = 0.408 lb. per second.

Examining the first foot width of plate we have :—

Temperature of water = 98° F.

Temperature of air = 60° F.

Saturation of air = 70 per cent.

It is assumed that after passing through the water the air is at the same temperature as the water and saturated to 100 per cent.

1 lb. of air at 60° F. and 100 per cent. sat. holds 0.011 lb. water  
 0.408 lb. of air at 60° F. and 70 per cent. sat. holds  $\frac{0.011 \times 70 \times 0.408}{100}$   
 = 0.00314 lb. water.

0.408 lb. air at 98° F. and 100 per cent. sat. holds 0.0415 × 0.408  
 = 0.017 lb. water.

∴ water taken up by 0.408 lb. air = 0.017 — 0.00314  
 = 0.01386 lb.

Latent heat of water at 98° F. = 1035 B.Th.U. per lb.

Heat taken from water by evaporation

= 0.01385 × 1035 = 14.38 B.Th.U.

Rise in temperature of air passing through water = 38° F.

Sensible heat taken up by air = 0.408 × 38 × 0.24  
 = 3.73 B.Th.U.

Total heat abstracted from water = 14.38 + 3.73  
 = 18.11 B.Th.U.

Fall in temperature of water =  $\frac{18.11 \text{ B.Th.U.}}{3.91 \text{ lb.}} = 4.63^\circ \text{ F.}$

Temperature of water after passing over 1 foot of plate =  
 98° — 4.63° = 93.37° F.

By similar calculations we have for each successive foot of plate up to 10 feet width, the following heat abstractions, water evaporated and water temperatures.

TABLE No. 5.

Velocity of water = 1 ft. per sec.

Depth of water =  $\frac{3}{4}$  in.

| At end of         | Heat abstracted.<br>(Total.) | Water evaporated.<br>(Total.) | Temperature.<br>° F. |
|-------------------|------------------------------|-------------------------------|----------------------|
|                   | B.Th.U.                      | lb.                           |                      |
| 1st foot of width | 18·11                        | ·01386                        | 93·37                |
| 2nd        "      | 32·52                        | ·02462                        | 89·68                |
| 3rd        "      | 45·07                        | ·03388                        | 86·47                |
| 4th        "    - | 55·67                        | ·04156                        | 83·75                |
| 5th        "      | 65·49                        | ·04872                        | 81·24                |
| 6th        "      | 73·86                        | ·05473                        | 79·10                |
| 7th        "      | 81·69                        | ·06044                        | 77·10                |
| 8th        "      | 88·3                         | ·06515                        | 75·41                |
| 9th        "    - | 94·59                        | ·06969                        | 73·44                |
| 10th       "      | 100·10                       | ·07370                        | 72·04                |

TABLE No. 6.

Velocity of water = 1·5 feet per sec.

Depth of water =  $\frac{3}{4}$  in.

| At end of         | Heat abstracted.<br>B.Th.U. Total. | Water evaporated.<br>Lb. Total. | Temperature<br>of Water. |
|-------------------|------------------------------------|---------------------------------|--------------------------|
| 1st foot of width | 18·11                              | ·01386                          | 94·91                    |
| 2nd        "      | 33·61                              | ·02550                          | 92·26                    |
| 3rd        "      | 47·49                              | ·03284                          | 89·89                    |
| 4th        "      | 60·13                              | ·04220                          | 87·73                    |
| 5th        "      | 71·55                              | ·05050                          | 85·78                    |
| 6th        "      | 82·15                              | ·05816                          | 83·97                    |
| 7th        "      | 91·86                              | ·06522                          | 82·32                    |
| 8th        "      | 100·82                             | ·07173                          | 80·79                    |
| 9th        "    - | 109·24                             | ·07783                          | 79·36                    |
| 10th       "      | 117·04                             | ·08347                          | 78·03                    |

TABLE 7.

Velocity of water = 2 feet per sec.

Depth of water =  $\frac{3}{4}$  in.

| At end of         | Heat abstracted.<br>B.Th.U. Total. | Water evaporated.<br>Lb. Total. | Temperature<br>of Water. |
|-------------------|------------------------------------|---------------------------------|--------------------------|
| 1st foot of width | 18·11                              | ·01386                          | 95·68                    |
| 2nd        "      | 34·10                              | ·02592                          | 93·26                    |
| 3rd        "      | 48·49                              | ·03666                          | 91·42                    |
| 4th        "    - | 62·18                              | ·0466                           | 89·67                    |
| 5th        "      | 74·57                              | ·0557                           | 88·09                    |
| 6th        "      | 87·33                              | ·06426                          | 86·55                    |
| 7th        "      | 98·35                              | ·07232                          | 85·14                    |
| 8th        "      | 108·61                             | ·07979                          | 83·83                    |
| 9th        "    - | 118·32                             | ·08685                          | 82·59                    |
| 10th       "      | 127·42                             | ·09351                          | 81·43                    |

CURVE No 2.

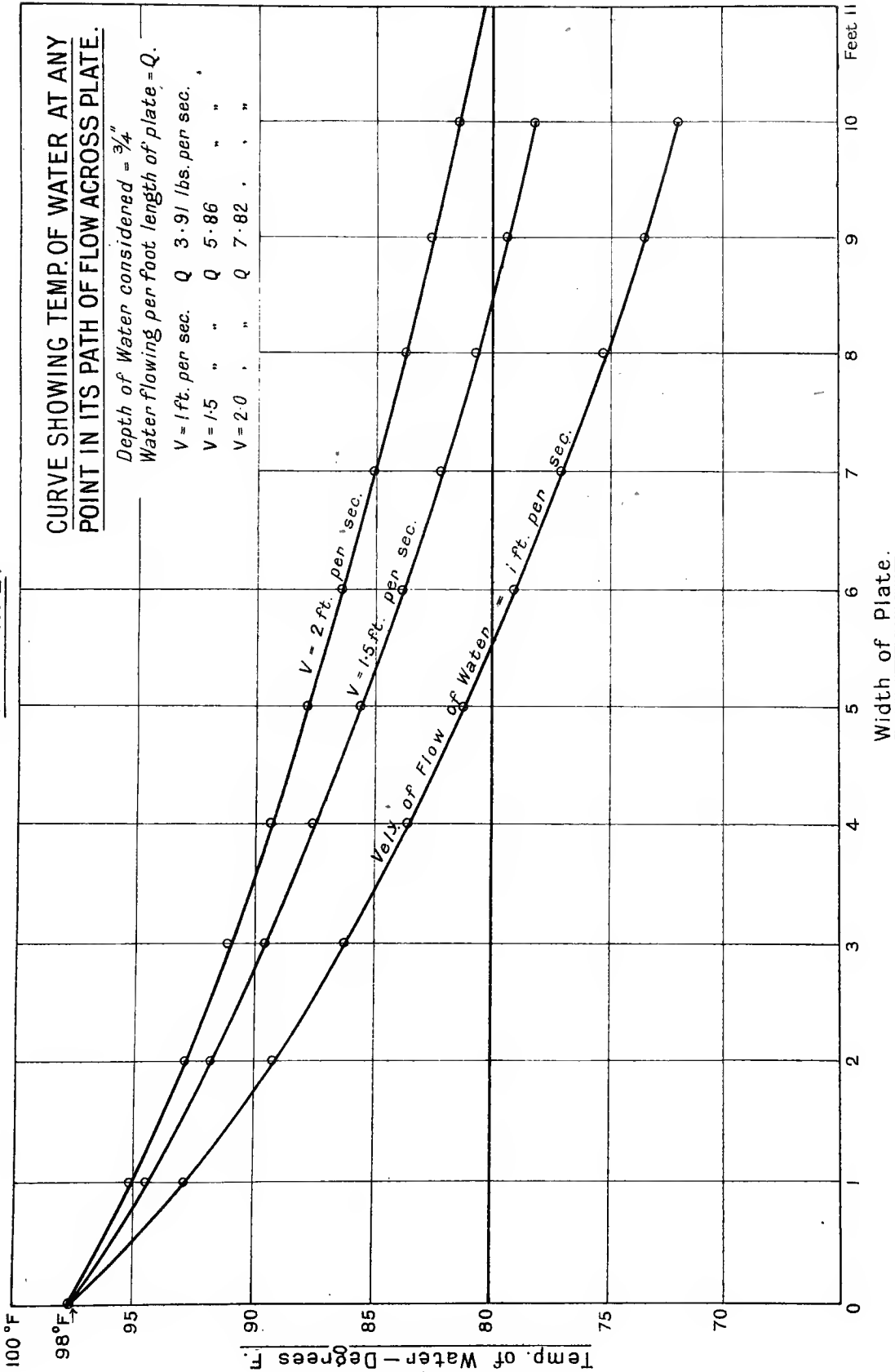


FIG. 14.



From Fig. 14 (Curve No. 2) we have width of plate required to cool from 98° F. to 80° F. for the three velocities taken, to be—

- (a) 5.55 feet for  $V = 1$  foot per second.
- (b) 8.45 feet for  $V = 1.5$  feet per second.
- (c) 11.10 feet for  $V = 2.0$  feet per second.

Therefore the area of plate required per 1,000 lbs. of water cooled per hour in the three cases becomes—

$$\begin{aligned}
 (a) \text{ 5.55 sq. ft. per 3.91 lb. per sec.} &= \frac{5.5 \times 1,000}{3.91 \times 60 \times 60} \\
 &= 0.394 \text{ square foot.} \\
 (b) \text{ 8.45 sq. ft. per 5.86 lb. per sec.} &= \frac{8.45 \times 1,000}{5.86 \times 60 \times 60} \\
 &= 0.400 \text{ square foot.} \\
 (c) \text{ 11.10 sq. ft. per 7.92 lb. per sec.} &= \frac{11.10 \times 1,000}{7.92 \times 60 \times 60} \\
 &= 0.394 \text{ square foot.}
 \end{aligned}$$

From these results it is apparent that, as far as area is concerned, the velocity of flow is of no consequence, the only effect of change of velocity being that a different width of plate is required, that is, the faster the flow, the wider the plate required to cool to equal temperature.

#### *Air efficiency.*

From Table 5 we have B.Th.U. abstracted in passing over first foot of plate = 18.11, which is equivalent to 100 per cent. efficiency over that part of the plate.

If, therefore, the air through each successive square foot of plate subtracted the same amount, we should have :—

$$\begin{aligned}
 \text{Heat abstracted over 10 feet width of plate} \\
 &= 18.11 \times 10 = 181.1 \text{ B.Th.U.}
 \end{aligned}$$

From the same table, however, we have the total heat abstracted = 100.10 B.Th.U.

$$\therefore \text{volumetric efficiency of air used} = \frac{100.1}{181.1} = 55.3 \text{ per cent.}$$

#### *Air required to cool 1,000 lb. water per hour.*

We have already found that to cool the above amount of water we require 0.394 square feet of plate, whilst from Table No. 3 we see that each square foot of plate (under  $\frac{3}{4}$  inch head of water) will pass 4.9 cubic feet per second.

$$\begin{aligned}
 \therefore \text{air required per 1,000 lb. of water per hour} \\
 &= 4.9 \text{ cubic feet} \times 0.394 \times 60 \\
 &= 116 \text{ cubic feet per minute.}
 \end{aligned}$$

#### *Power required.*

If we have  $\frac{3}{4}$  inch water over the plates we shall probably require about  $1\frac{1}{4}$  inch water pressure at the fan to overcome pipe friction, &c.

27.6 inches water press = 1 pound per square inch.

$$1\frac{1}{4} \text{ inches water press} = \frac{1 \times 12.5}{27.6} = 0.0454 \text{ lb. per square inch.}$$

$$= 6.53 \text{ lb. per square foot.}$$

and theoretical power of fan

$$= \frac{6.53 \times 116}{33,000} = 0.02294 \text{ H.P.}$$

Assuming efficiency of fan to be 65 per cent., then actual power required

$$= \frac{0.02294 \times 100}{65} = 0.0353 \text{ H.P.}$$

*Summary.*

To cool 1,000 lb. water per hour from 98° F. to 80° F. with air at 60° F. and 70 per cent. saturation, we require

0.394 square feet of  $\frac{3}{8}$ -in. plate perforated with  $\frac{1}{8}$  in. diameter holes spaced  $\frac{3}{8}$  in. centre to centre,

116 cubic feet of air per minute at a pressure of  $1\frac{1}{4}$  in. of water, and

0.0353 horse power at the fan shaft.

*Example.*

1,000-k.w. generator set. Steam consumption, 15 lb. per k.w. hour. Circulating water entering cooler, 98° F. Circulating water entering condenser, 80° F. Ratio of cooling water to steam condenser, 60 : 1; air temperature, 60° F., and saturation, 70 per cent.

$$\text{Water to cooler} = 1,000 \text{ k.w.} \times 15 \text{ lb. per k.w.} \times 60$$

$$= 900,000 \text{ lb. per hour.}$$

$$\text{Area of bubbler plates required} = 0.394 \times 900 = 354.6 \text{ sq. ft.}$$

Plates may be 5.5 ft. wide  $\times$  64 feet long,  
8.45 ft. wide  $\times$  42 feet long, or  
11.0 ft. wide  $\times$  32 feet long.

$$\text{Volume of air required} = 116 \times 900 = 104,400 \text{ cubic feet per minute.}$$

$$\text{Power required} = 0.0353 \times 900 = 31.77 \text{ H.P.}$$

$$= 3.177 \text{ per cent. of power of generator set.}$$

*Velocity, 1 foot per second.*

From Table 2 we have water passing = 3.91 lb. per sec.

From Table No. 3 we have air passing through 1 square foot of plate = 4.9 cubic feet per second.  
= 0.408 lb. per second.

1st foot of plate :—

Temperature of water = 98° F.

Temperature of air = 60° F.

Saturation of water = 50 per cent.

1 lb. of air at 60° F. and 100 per cent. saturation holds 0.011 lb. water

$$0.408 \text{ lb. of air at } 60^\circ \text{ F. and 100 per cent. saturation holds } \frac{0.011 \times 50 \times 0.408}{100}$$

$$= 0.002244 \text{ lb. water.}$$

CURVE No 3.

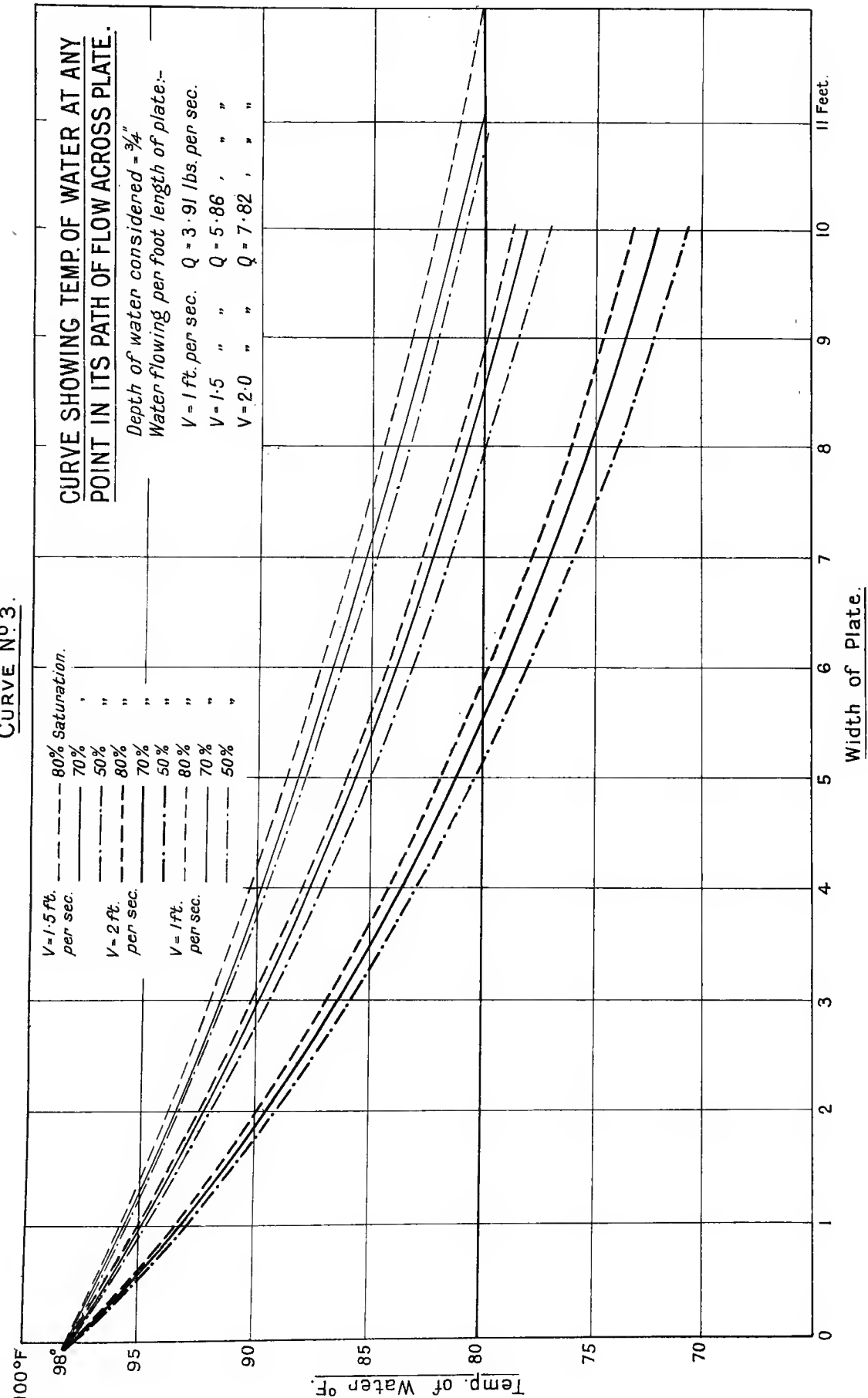


FIG. 15.



|                                                           |                                                                     |
|-----------------------------------------------------------|---------------------------------------------------------------------|
| ·408 lb. air at 98° F. and 100 per cent. saturation holds | ·0415 = 0·408                                                       |
|                                                           | = ·017 lb. water.                                                   |
| ∴ water taken up by ·408 lb. air                          | = 0·017 — 0·002244                                                  |
|                                                           | = 0·14756 lb.                                                       |
| Latent heat of water at 98° F.                            | = 1,035 B.Th.U. per lb.                                             |
| Heat taken from water by evaporation                      | = ·014756 = 1035                                                    |
|                                                           | = 15·27 B.Th.U.                                                     |
| Rise in temperature of air passing through water          | = 38° F.                                                            |
| Sensible heat taken up by air                             | = 0·408 × 38 × 0·24                                                 |
|                                                           | = 3·73 B.Th.U.                                                      |
| Total heat abstracted from water                          | = 15·27 + 3·73                                                      |
|                                                           | = 19 B.Th.U.                                                        |
| Fall in temperature of water =                            | $\frac{19·00 \text{ B.Th.U.}}{3·91 \text{ lb.}} = 4·86° \text{ F.}$ |
| Temperature of water after passing over 1 foot of plate   |                                                                     |
|                                                           | = 98° — 4·86 = 93·14° F.                                            |

TABLE 5a.

Velocity of water, 1 foot per second. Depth of water,  $\frac{3}{4}$  in.

| At end of  | Heat abstracted<br>(Total), B.Th.U. | Water evaporated,<br>lb. Total. | Temperature.<br>° F. |
|------------|-------------------------------------|---------------------------------|----------------------|
| 1st foot - | 19·00                               | ·014756                         | 93·14                |
| 2nd „ -    | 34·46                               | ·026412                         | 89·19                |
| 3rd „ -    | 47·63                               | ·036328                         | 85·82                |
| 4th „ -    | 59·10                               | ·044904                         | 82·89                |
| 5th „ -    | 69·35                               | ·052560                         | 80·27                |
| 6th „ -    | 78·89                               | ·059316                         | 77·83                |
| 7th „ -    | 87·03                               | ·065422                         | 75·75                |
| 8th „ -    | 94·57                               | ·071158                         | 73·82                |
| 9th „ -    | 101·28                              | ·076274                         | 72·11                |
| 10th „ -   | 107·33                              | ·080900                         | 70·60                |

TABLE 6a.

Velocity of water 1·5 feet per second. Depth of water,  $\frac{3}{4}$  in.

| At end of  | Heat abstracted<br>(Total), B.Th.U. | Water evaporated,<br>lb. Total. | Temperature.<br>° F. |
|------------|-------------------------------------|---------------------------------|----------------------|
| 1st foot - | 19·00                               | ·014756                         | 94·76                |
| 2nd „ -    | 35·33                               | ·027232                         | 91·97                |
| 3rd „ -    | 50·16                               | ·038488                         | 89·44                |
| 4th „ -    | 63·44                               | ·078524                         | 87·18                |
| 5th „ -    | 75·48                               | ·057530                         | 85·13                |
| 6th „ -    | 86·72                               | ·065930                         | 83·19                |
| 7th „ -    | 95·86                               | ·072506                         | 81·63                |
| 8th „ -    | 105·48                              | ·079662                         | 79·99                |
| 9th „ -    | 114·50                              | ·086418                         | 78·45                |
| 10th „ -   | 122·98                              | ·092774                         | 77                   |

TABLE 7a.  
Velocity of water, 2 feet per second. Depth of water,  $\frac{3}{4}$  in.

| At end of | Heat abstracted<br>(Total), B.Th.U. | Water evaporated,<br>lb. Total. | Temperature.<br>° F. |
|-----------|-------------------------------------|---------------------------------|----------------------|
| 1st foot  | 19.00                               | .014756                         | 95.57                |
| 2nd "     | 35.80                               | .027602                         | 93.42                |
| 3rd "     | 51.35                               | .039458                         | 91.45                |
| 4th "     | 65.73                               | .050314                         | 89.62                |
| 5th "     | 79.03                               | .060350                         | 87.92                |
| 6th "     | 91.86                               | .069976                         | 86.28                |
| 7th "     | 103.73                              | .078882                         | 84.76                |
| 8th "     | 114.69                              | .097058                         | 83.36                |
| 9th "     | 124.88                              | .094514                         | 82.06                |
| 10th "    | 134.54                              | .101770                         | 80.82                |

From Fig. 15 (Curve No. 3) we have width of plate required to cool from 98° F. to 80° F. for the three velocities taken and 50 per cent. saturation.

- (a) 5.1 feet for  $V = 1$  foot per second.
- (b) 7.9 feet for  $V = 1.5$  feet per second.
- (c) 10.75 feet for  $V = 2$  feet per second.

∴ the area of plate required for 1,000 lb. of water cooled per hour in the three cases becomes

$$(a) \ 5.1 \text{ square feet per } 3.91 \text{ lb. per second} \\ = \frac{5.1 \times 1000}{3.19 \times 60 \times 60} = 0.363 \text{ sq. ft.}$$

$$(b) \ 7.9 \text{ square feet per } 5.86 \text{ lb. per second} \\ = \frac{7.9 \times 1000}{5.86 \times 60 \times 60} = 0.374 \text{ sq. ft.}$$

$$(c) \ 10.75 \text{ square feet per } 7.82 \text{ lb. per second} \\ = \frac{10.75 \times 1000}{7.82 \times 60 \times 60} = 0.379 \text{ sq. ft.}$$

*Air efficiency.*

From Table 5a we have B.Th.U. abstracted in passing over first foot of plate = 19 which is equivalent to 100 per cent. efficiency over that part of the plate.

If, therefore, the air through each successive square foot of plate abstracted the same amount, we should have

$$\text{Heat abstracted over 10 feet width of plate} \\ = 19 \times 10 = 190 \text{ B.Th.U.}$$

From the same table, however, we have total heat abstracted  
= 107.33 B.Th.U.

$$\therefore \text{volumetric efficiency of air used} = \frac{107.33}{190} = 56.4 \text{ per cent.}$$

*Air required to cool 1,000 lb. water per hour.*

We have already found that to cool the above amount of water we require 0.374 sq. ft. of plate, whilst from Table 3 we see that each square foot of plate (under  $\frac{3}{4}$  in. head of water) will pass 4.9 cubic feet per second.

$$\begin{aligned}\therefore \text{air required per 1,000 lb. water per hour} \\ &= 4.9 \text{ cubic feet} \times 0.374 \times 60 \\ &= 110 \text{ cubic feet per minute.}\end{aligned}$$

*Power required.*

If we have  $\frac{3}{4}$  in. of water over the plates we shall probably require about  $1\frac{1}{4}$  in. water pressure at the fan to overcome pipe friction, &c.

$$27.6 \text{ inches water pressure} = 1 \text{ lb. per sq. in.}$$

$$\begin{aligned}1\frac{1}{4} \text{ inches water pressure} &= \frac{1 \times 1.25}{27.6} = 0.0454 \text{ lb. per sq. in.} \\ &= 6.53 \text{ lb. per sq. ft.}\end{aligned}$$

and theoretical power of fan

$$= \frac{6.53 \times 110}{33000} = 0.0218 \text{ H.P.}$$

Assume efficiency of fan to be 65 per cent., then actual power required

$$= \frac{0.0218 \times 100}{65} = 0.0336 \text{ H.P.}$$

*Summary.*

To cool 1,000 lb. of water per hour from 98° F. to 80° F., with air at 60° F. and 50 per cent. saturation, we require

0.374 sq. ft. of  $\frac{3}{8}$  in. plate perforated with  $\frac{1}{8}$  in. diameter holes spaced  $\frac{3}{8}$  in. centre to centre.

110 cubic feet of air per minute at a pressure of  $1\frac{1}{4}$  in. of water and 0.0336 horse power at fan shaft.

*Example.*

1,000 k.w. generator set. Steam consumption, 15 lb. per k.w. hr. Circulating water entering cooler at 98° F. Circulating water entering condenser at 80° F. Ratio of cooling water to steam condensed 60 : 1, air temperature 60° F. and 50 per cent. saturation.

$$\begin{aligned}\text{Water to cooler} &= 1,000 \text{ k.w.} \times 15 \text{ lb.} \times 60 \\ &= 900,000 \text{ lb. per hour.}\end{aligned}$$

$$\text{Area of bubble plates required} = 0.374 \times 900 = 336 \text{ sq. ft.}$$

$$\text{Plates may be } 5.1 \text{ feet wide} \times 66 \text{ feet long.}$$

$$7.9 \text{ feet wide} = 42.6 \text{ feet long.}$$

$$10.75 \text{ feet wide} \times 31.3 \text{ feet long.}$$

$$\text{Volume of air required} = 110 \times 900 = 99,000 \text{ cubic feet per min.}$$

$$\text{Power required} = 0.0336 \times 900 = 30.2 \text{ h.p.}$$

$$= 3.02 \text{ per cent. of power of generator set.}$$

Velocity, 1 foot per second. Depth of water,  $\frac{3}{4}$  in.; saturation, 80 per cent.

1 lb. of air at 60° F. and 100 per cent. saturation holds .011 lb. water

.408 lb. of air at 60° F. and 80 per cent. saturation holds  $\frac{.011 \times 80 \times .408}{100}$

= .00359 lb. water.

.408 lb. of air at 98° F. and 100 per cent. saturation holds .0415 × .408

= .017 lb. water.

∴ water taken up by 0.48 lb. air = .017 - .00359

= .01341 lb.

Latent heat of water at 98° F. = 1035 B.Th.U.

Heat taken from water by evaporation = .01341 × 1035 = 13.88 B.Th.U.

Rise in temperature of air passing through water = 38° F.

Sensible heat taken up by air = .408 × 38 × .24 = 3.73 B.Th.U.

Total heat abstracted from water = 13.88 + 3.73 = 17.61 B.Th.U.

Fall in temperature of water =  $\frac{17.61}{3.91} = 4.5^\circ \text{ F.}$

Temperature of water after passing over 1 foot of plate

= 98° - 4.5° F. = 93.5° F.

TABLE No. 5b.

Velocity, 1 ft. per second. Depth of water,  $\frac{3}{4}$  in.

| At end of | Heat abstracted<br>(Total), B.Th.U. | Water evaporated,<br>lb. Total. | Temperature,<br>° F. |
|-----------|-------------------------------------|---------------------------------|----------------------|
| 1st foot  | 17.61                               | .013410                         | 93.5                 |
| 2nd „     | 31.77                               | .02389                          | 89.88                |
| 3rd „     | 43.74                               | .03258                          | 86.82                |
| 4th „     | 54.27                               | .04023                          | 84.12                |
| 5th „     | 63.57                               | .04686                          | 81.74                |
| 6th „     | 71.80                               | .05269                          | 79.64                |
| 7th „     | 79.24                               | .05795                          | 77.74                |
| 8th „     | 85.96                               | .06271                          | 76.00                |
| 9th „     | 91.91                               | .06689                          | 74.48                |
| 10th „    | 97.28                               | .07066                          | 73.10                |

TABLE No. 6b.

Velocity, 1.5 feet per second. Depth of water,  $\frac{3}{4}$  in.

| At end of | Heat abstracted<br>(Total), B.Th.U. | Water evaporated,<br>lb. Total. | Temperature,<br>° F. |
|-----------|-------------------------------------|---------------------------------|----------------------|
| 1st foot  | 17.61                               | .013410                         | 94.93                |
| 2nd "     | 32.65                               | .02462                          | 92.36                |
| 3rd "     | 46.23                               | .03463                          | 90.04                |
| 4th "     | 58.44                               | .04354                          | 87.97                |
| 5th "     | 69.60                               | .05162                          | 88.06                |
| 6th "     | 79.80                               | .05895                          | 84.32                |
| 7th "     | 89.18                               | .06566                          | 82.72                |
| 8th "     | 97.93                               | .07191                          | 81.23                |
| 9th "     | 106.11                              | .07774                          | 79.84                |
| 10th "    | 113.21                              | .08266                          | 78.63                |

TABLE No. 7b.

Velocity, 2 feet per second. Depth of water,  $\frac{3}{4}$  in.

| At end of | Heat abstracted<br>(Total), B.Th.U. | Water evaporated,<br>lb. Total. | Temperature,<br>° F. |
|-----------|-------------------------------------|---------------------------------|----------------------|
| 1st foot  | 17.61                               | .013410                         | 95.75                |
| 2nd "     | 33.11                               | .02496                          | 93.79                |
| 3rd "     | 47.44                               | .03557                          | 91.95                |
| 4th "     | 60.87                               | .04548                          | 90.21                |
| 5th "     | 73.13                               | .05443                          | 88.64                |
| 6th "     | 84.65                               | .06278                          | 87.16                |
| 7th "     | 95.52                               | .07066                          | 85.77                |
| 8th "     | 105.54                              | .07777                          | 84.49                |
| 9th "     | 115.14                              | .08466                          | 83.26                |
| 10th "    | 124.02                              | .09097                          | 82.13                |

Width of plate required (from Curve No. 3)—

- (a) 5.85 feet for  $V = 1$  foot per second.  
 (b) 8.9 feet for  $V = 1.5$  feet per second.  
 (c) 12 feet for  $V = 2$  feet per second.

Areas of plate required per 1,000 lb. of water cooled per hour

(a) 5.85 sq. ft. per 3.91 lb. per second

$$= \frac{5.85 \times 1000}{3.91 \times 60 \times 60} = 0.41 \text{ sq. ft.}$$

(b) 8.9 sq. ft. per 5.86 lb. per second

$$= \frac{8.9 \times 1000}{5.86 \times 60 \times 60} = 0.41 \text{ sq. ft.}$$

(c) 12 square feet per 7.82 lb. per second

$$= \frac{14 \times 1000}{7.82 \times 60 \times 60} = 0.41 \text{ sq. ft.}$$

*Air efficiency.*

B.T.U. abstracted over 1st foot of plate = 17.61 equivalent to 100 per cent. efficiency.

Heat abstracted over 10 feet of plate =  $17.61 \times 10 = 176.1$  B.T.U.

Total heat abstracted from Table 5b = 97.28.

$$\text{Volumetric efficiency} = \frac{97.28}{176.1} = 55.1 \text{ per cent.}$$

*Air required to cool 1,000 lb. water per hour.*

We require 0.41 square feet of plate. From Table 3 each square foot of plate will pass 4.9 cubic feet per second.

$\therefore$  air required per 1,000 lb. of water per hour

$$\begin{aligned} &= 4.9 \times 0.41 \times 60 \\ &= 120 \text{ cubic feet per minute.} \end{aligned}$$

*Power required.*

$$\text{Theoretical power of fan} = \frac{6.53 \times 120}{33000} = 0.238 \text{ h.p.}$$

$$\begin{aligned} \text{and at 65 per cent. efficiency actual power} &= \frac{0.238 \times 100}{65} \\ &= 0.367 \text{ h.p.} \end{aligned}$$

*Summary.*

To cool 1,000 lb. water per hour from 98° to 80° F., air at 60° and 80 per cent. saturation, we require

0.41 square feet of  $\frac{3}{4}$  in. perforated plate  $\frac{1}{8}$  in. diameter holes and  $\frac{3}{8}$  in. pitch.

120 cubic feet of air per minute at a pressure of  $1\frac{1}{4}$  in. of water and 0.367 h.p. at the fan shaft.

*Example.*

Taking the same example as before—

Water to soaker = 900,000 lb. per hour.

Area of bubbler plates =  $0.41 \times 900 = 369$  sq. ft.

Plates may be 5.85 feet wide  $\times$  63.2 feet long.

8.9 feet wide  $\times$  41.5 feet long.

12 feet wide  $\times$  30.75 feet long.

Volume of air required =  $120 \times 900 = 108,00$  cu. ft. per min.

Power required =  $0.367 \times 900 = 33$  h.p.

= 3.3 per cent. of power of generator set.







To be purchased through any Bookseller or directly from  
H.M. STATIONERY OFFICE at the following addresses:  
IMPERIAL HOUSE, KINGSWAY, LONDON, W.C. 2, and  
28, ABINGDON STREET, LONDON, S.W. 1;  
37, PETER STREET, MANCHESTER;  
1, ST. ANDREW'S CRESCENT, CARDIFF;  
or 23, FORTH STREET, EDINBURGH.

---

*Price 5s. od. Net.*